PHOTON-NUMBER-RESOLVING IMAGERS AND SENSORS BASED ON SUPERCONDUCTING NANOWIRES

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TECHNICAL PAPERS

THE SECONDARY EMISSION MULTIPLIER—A NEW ELECTRONIC DEVICE*

By
V. K. Zworykin, G. A. Morton, and L. Malter
(RCA Manufacturing Company, RCA Victor Division, Camden, New Jersey)

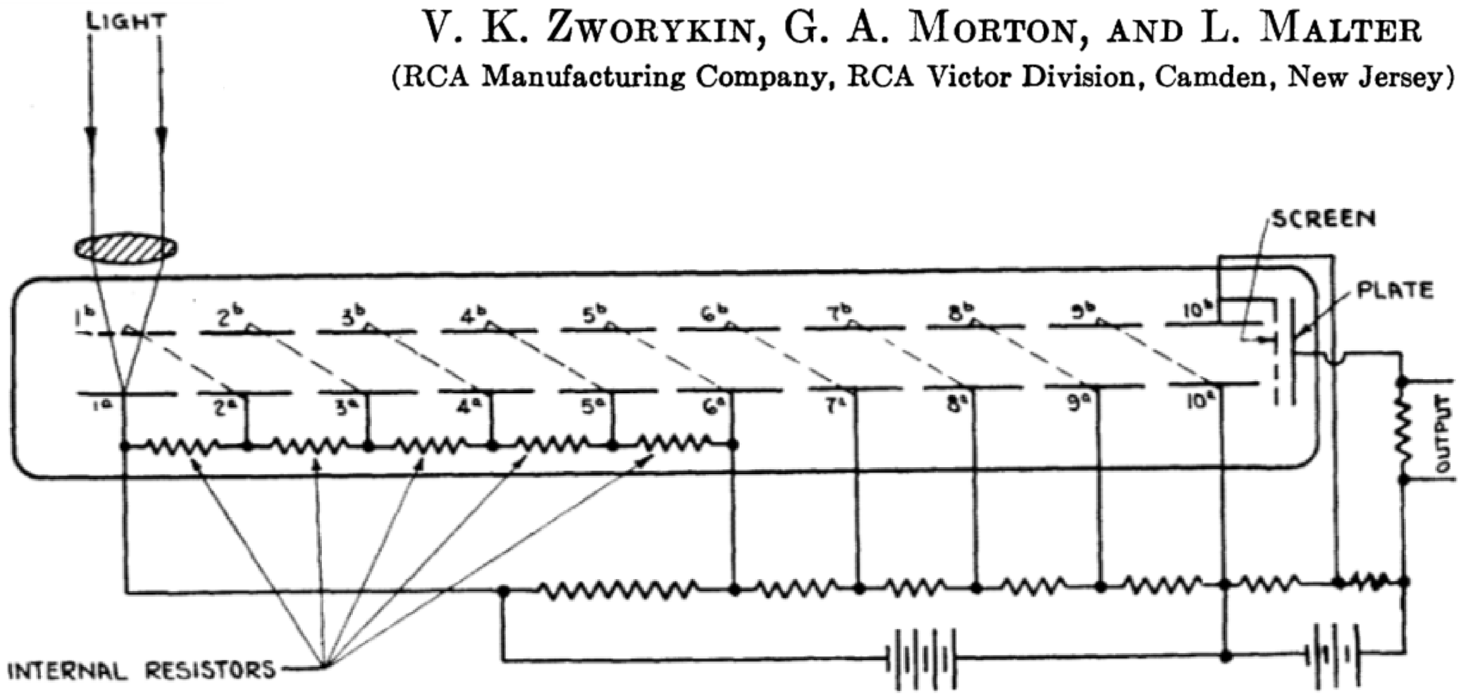


Fig. 9

HOW TO DETECT A PHOTON WITH A SUPERCONDUCTOR?

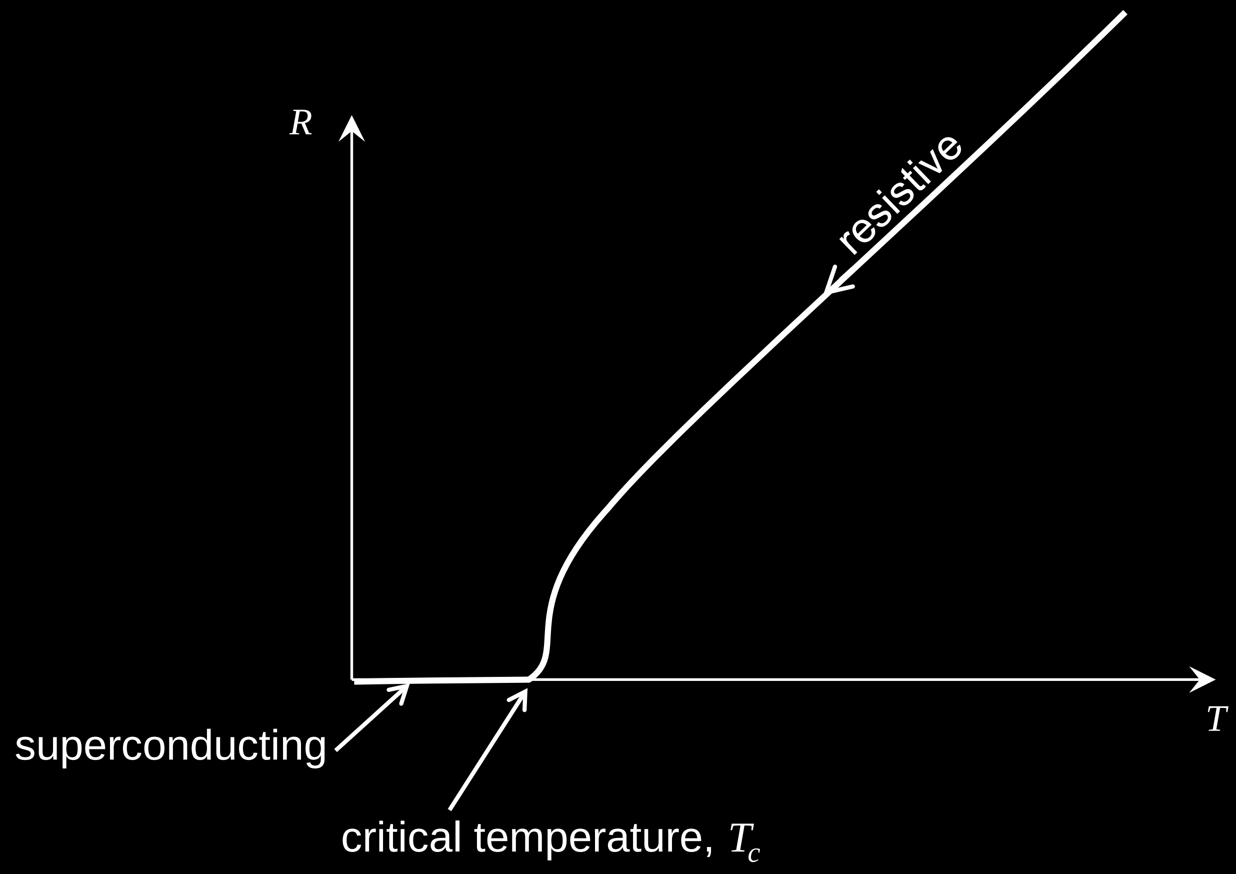
Why are Superconductors Interesting?

- Zero resistance
- Exclusion of magnetic field
- Strong nonlinearity

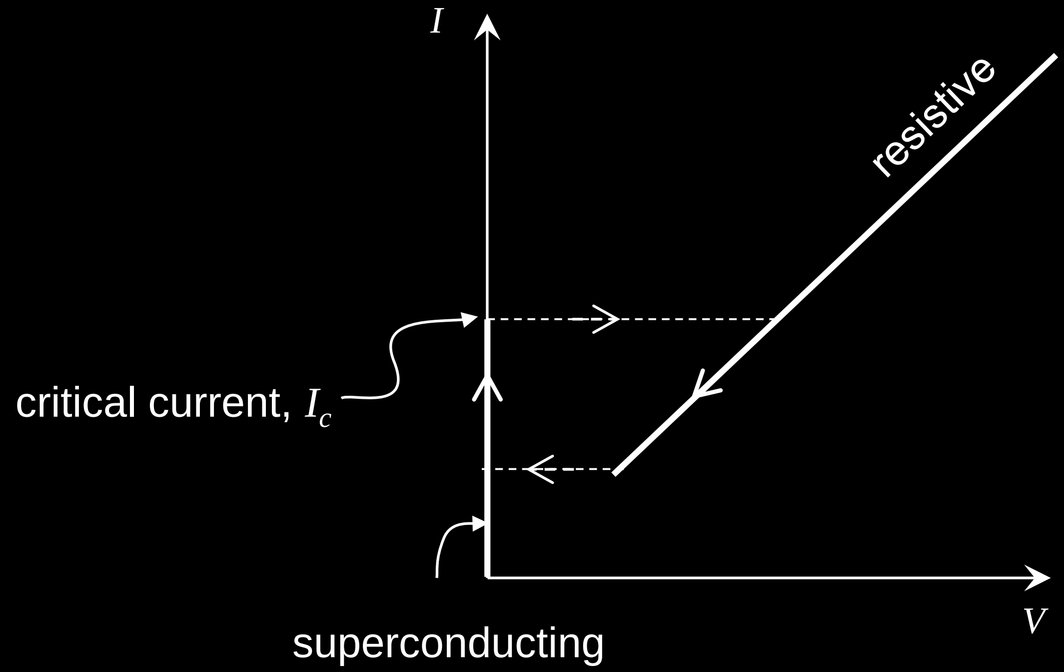
Why are Superconductors Interesting?

- Zero resistance
- Exclusion of magnetic field
- Strong nonlinearity

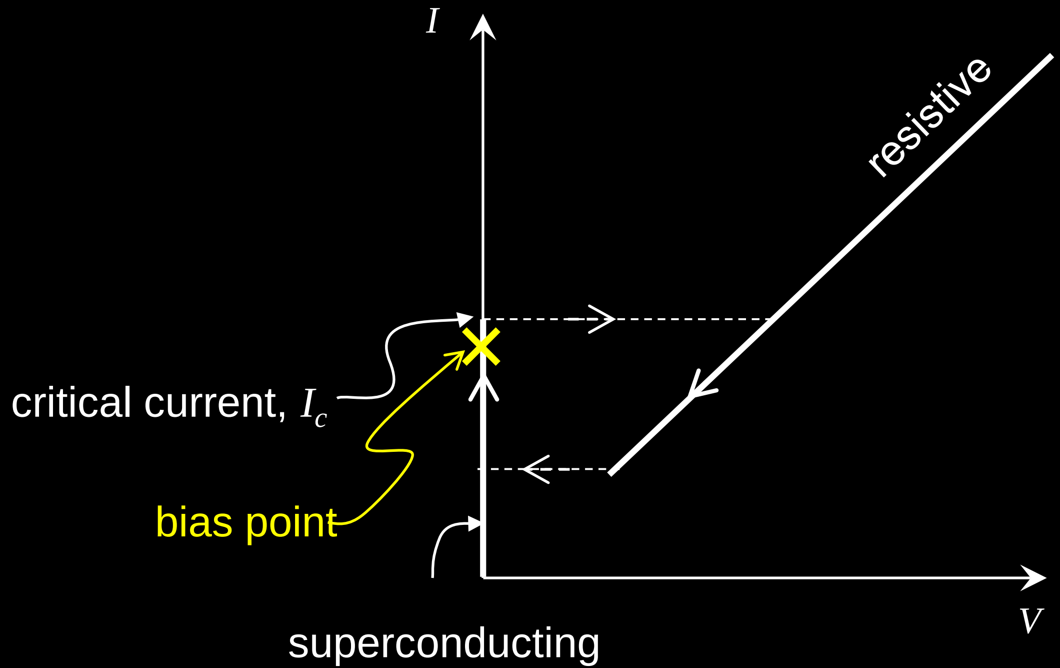
Analog Amplifiers



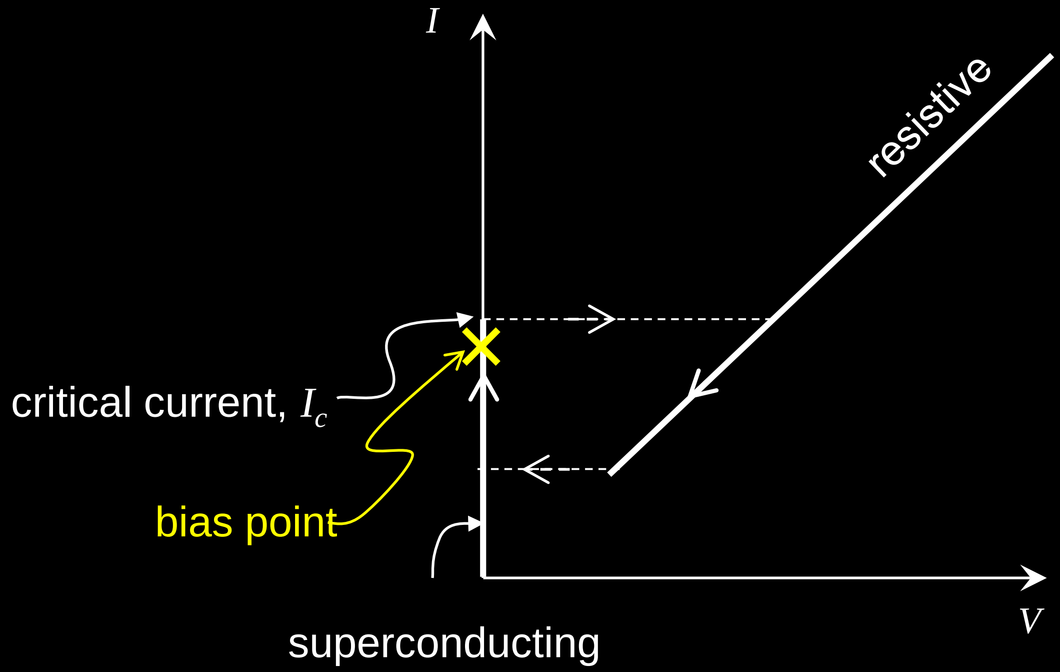
Comparison-Based Device

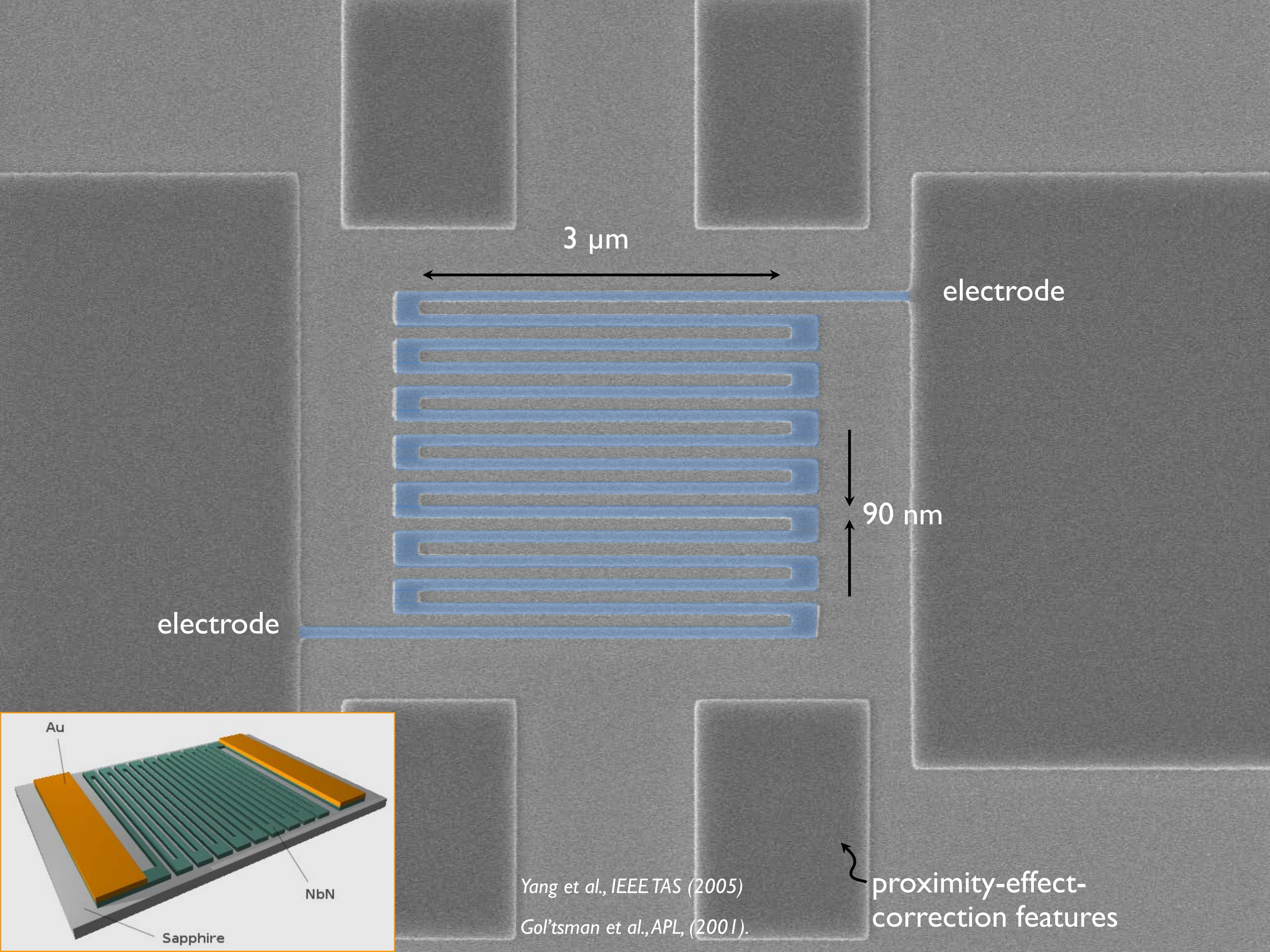


Comparison-Based Device



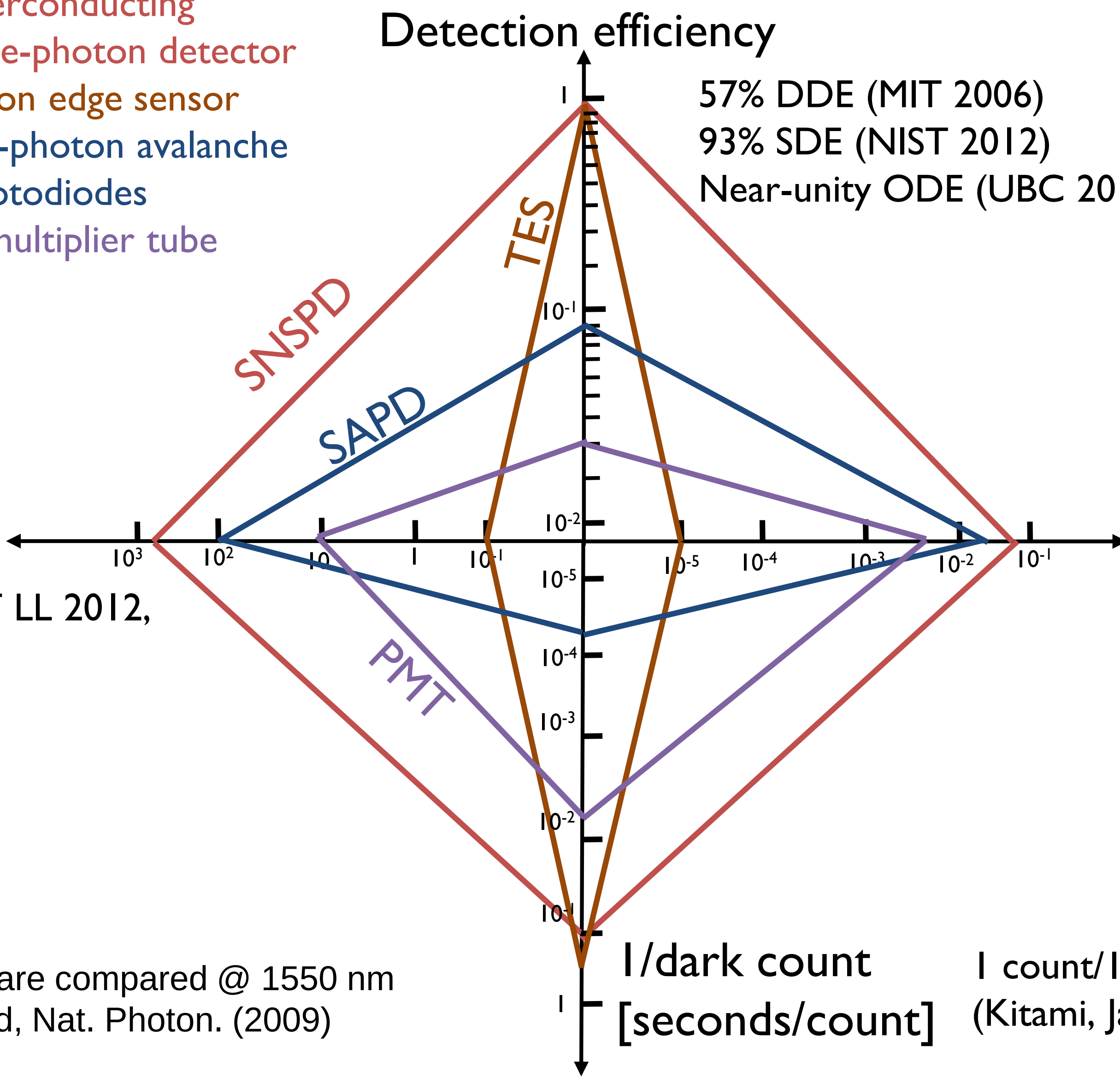
Comparison-Based Device




3 µm
electrode
90 nm
electrode
Au
NbN
Sapphire
Yang et al., IEEE TAS (2005)
Gol'tsman et al., APL, (2001).
proximity-effect-
correction features

Detector metrics

SNSPD – Superconducting nanowire single-photon detector
TES – Transition edge sensor
SAPD – Single-photon avalanche photodiodes
PMT – Photomultiplier tube



57% DDE (MIT 2006)
93% SDE (NIST 2012)
Near-unity ODE (UBC 2015)

500 Mcps (MIT LL 2012, 4-pixel array)

1/(18 ps) (Yale 2012)
1/(24 ps) (MIT 2015)

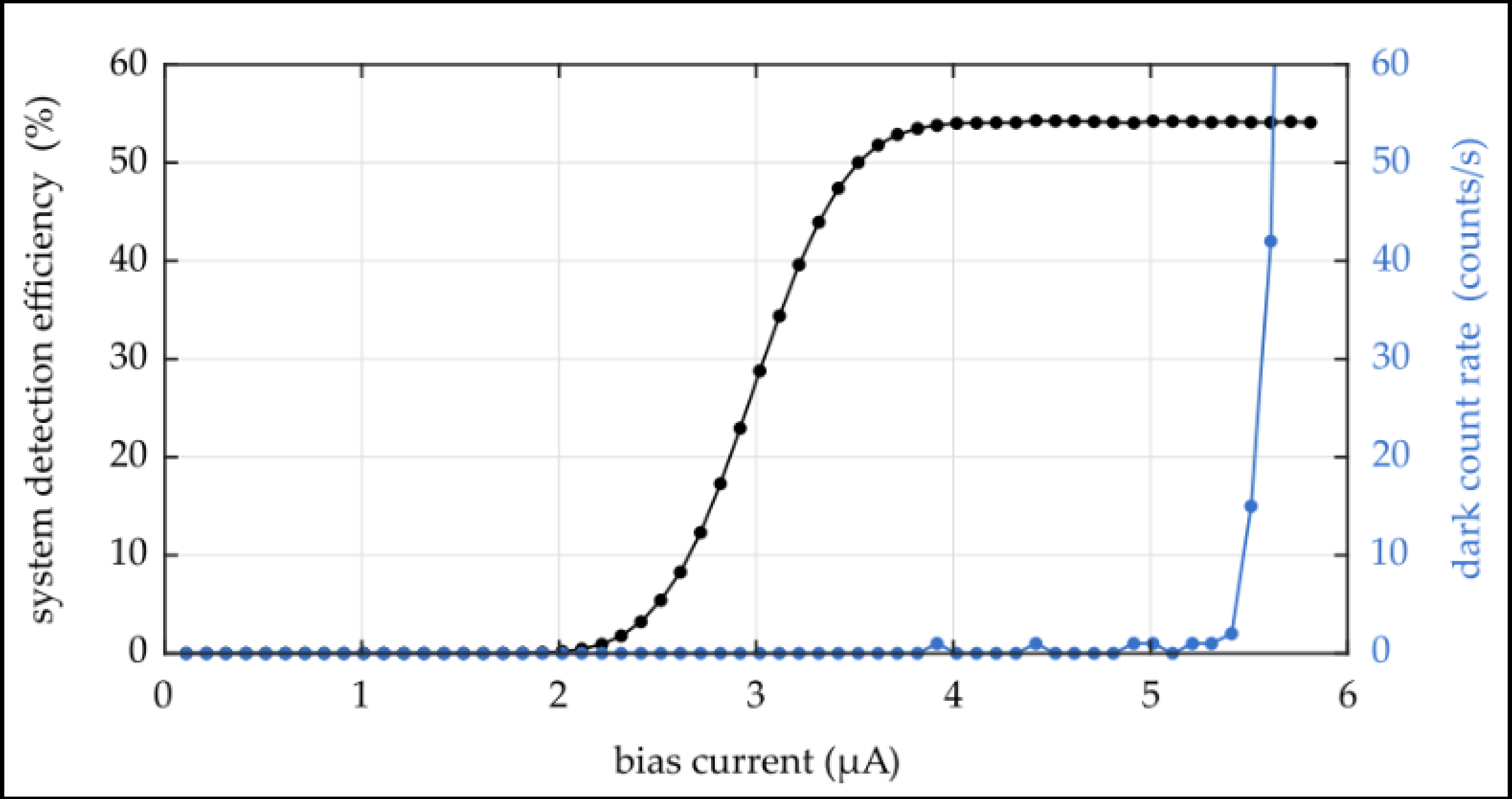
1 count/10^3 seconds (Kitami, Japan 2015)

Detector metrics are compared @ 1550 nm based on Hadfield, Nat. Photon. (2009)

Dark Counts

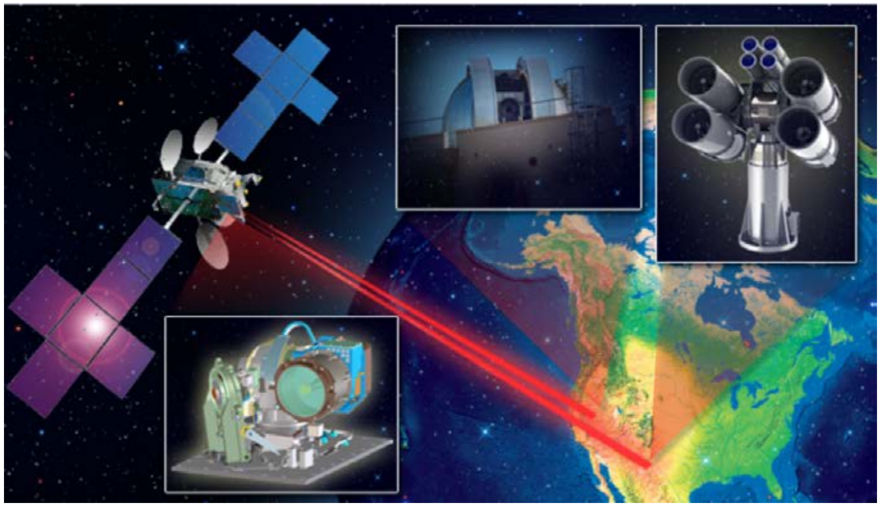
E.E. Wollman et al, Optics Express 25, 26792 (2017) (JPL group)

Dark counts of 6 counts per day were demonstrated at 4K.



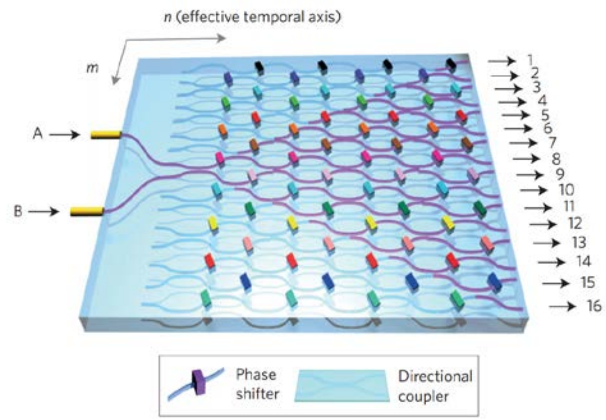
Applications

Space Communications



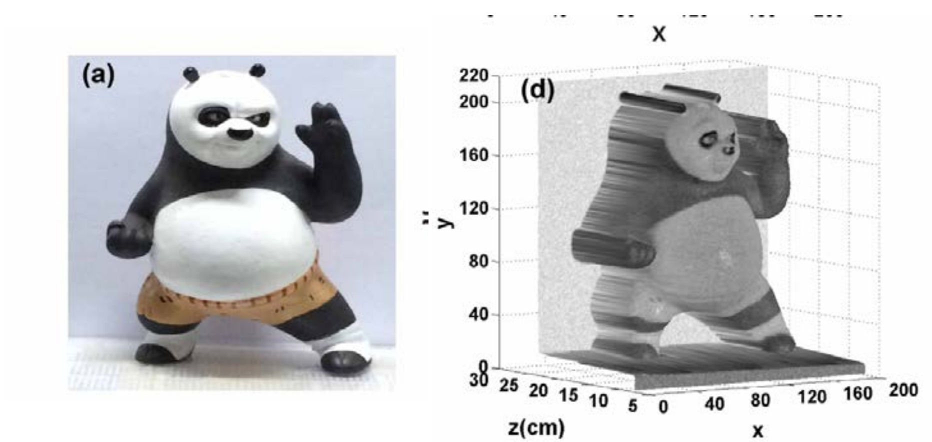
Lincoln Lab/JPL

Quantum walk/simulation



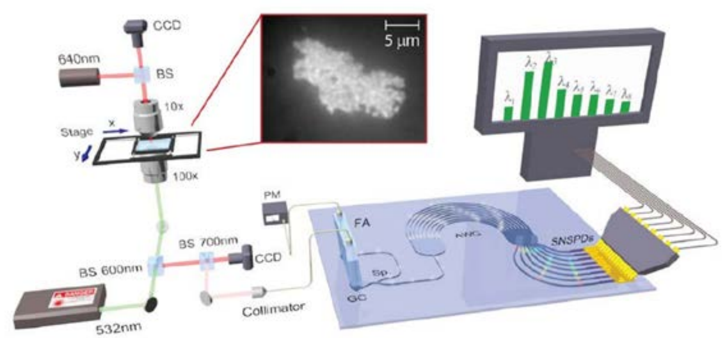
Crespi, et al., Nat. Photon 7, 322–328 (2013)

LIDAR



Zhou et al., Opt. Expr. 23, 14603 (2015)

Single-photon spectrometer



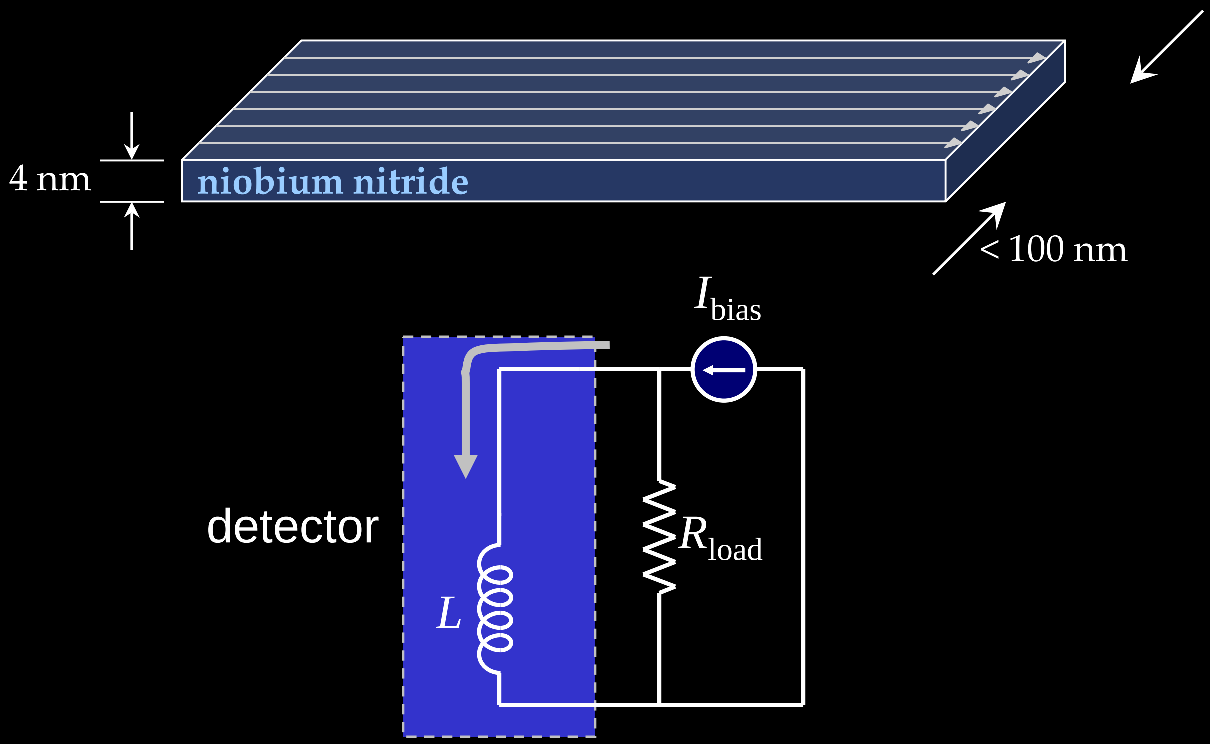
Kahl, et al., arXiv:1609.07857 (2016)

DEVICE OPERATION

Detection Mechanism

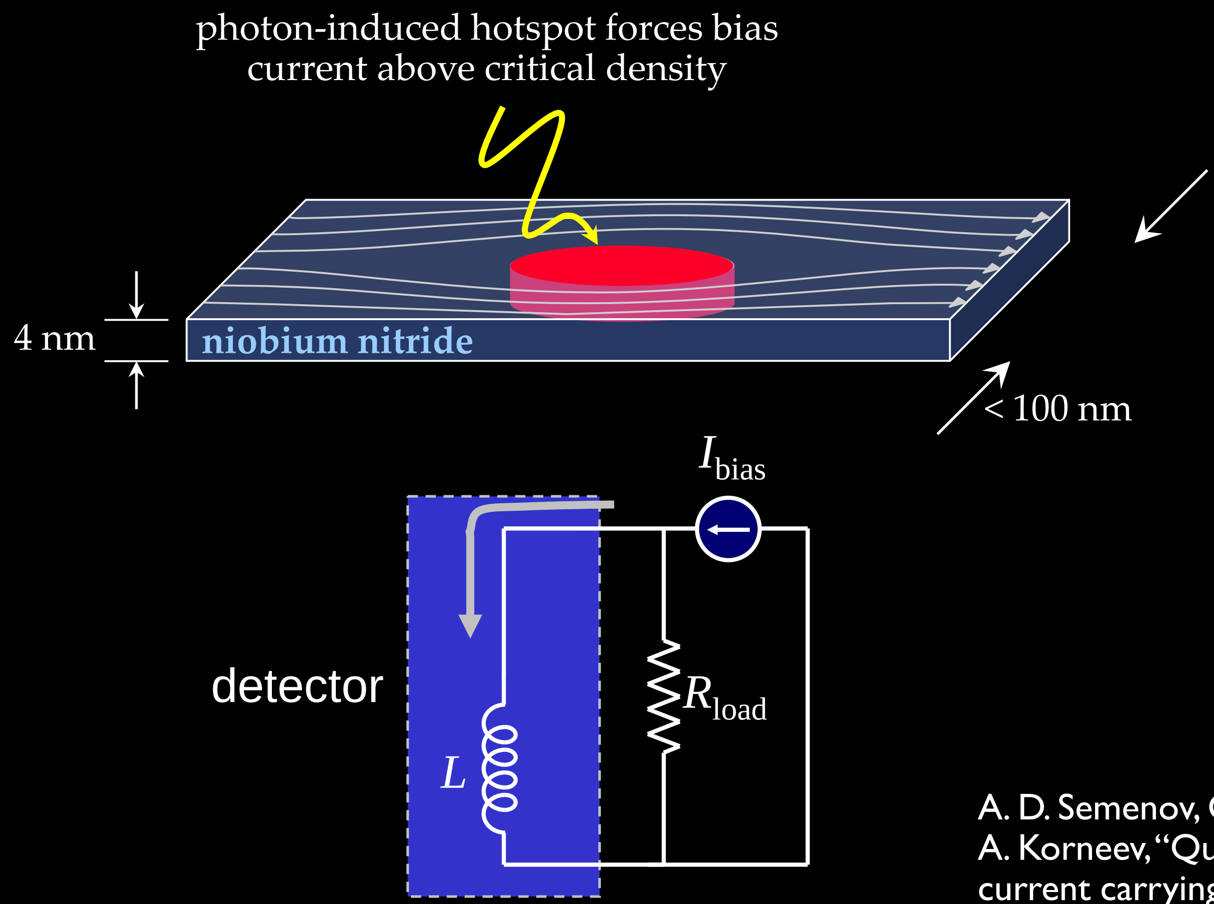
Critical Temperature ~ 11 K

superconductor is biased near its transition



Absorption

Critical Temperature ~ 11 K

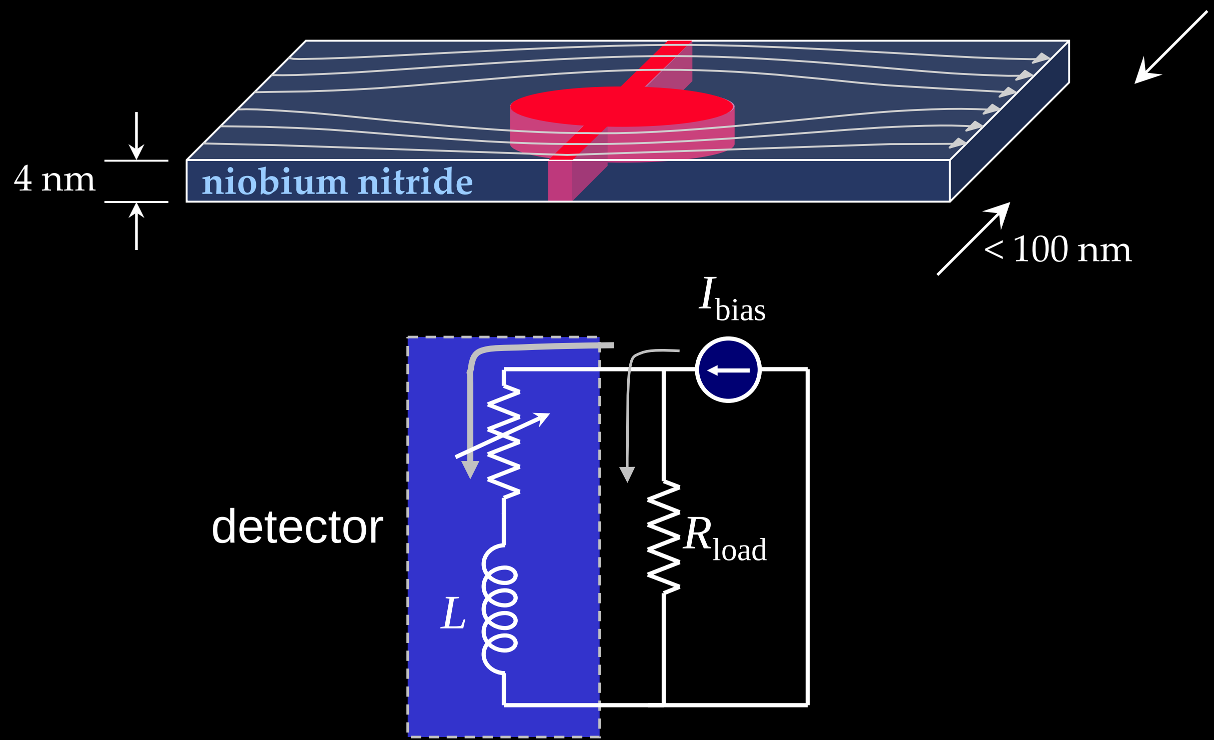


A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica C, vol. 351*, pp. 349–356, 2001.

Breakdown

Critical Temperature ~ 11 K

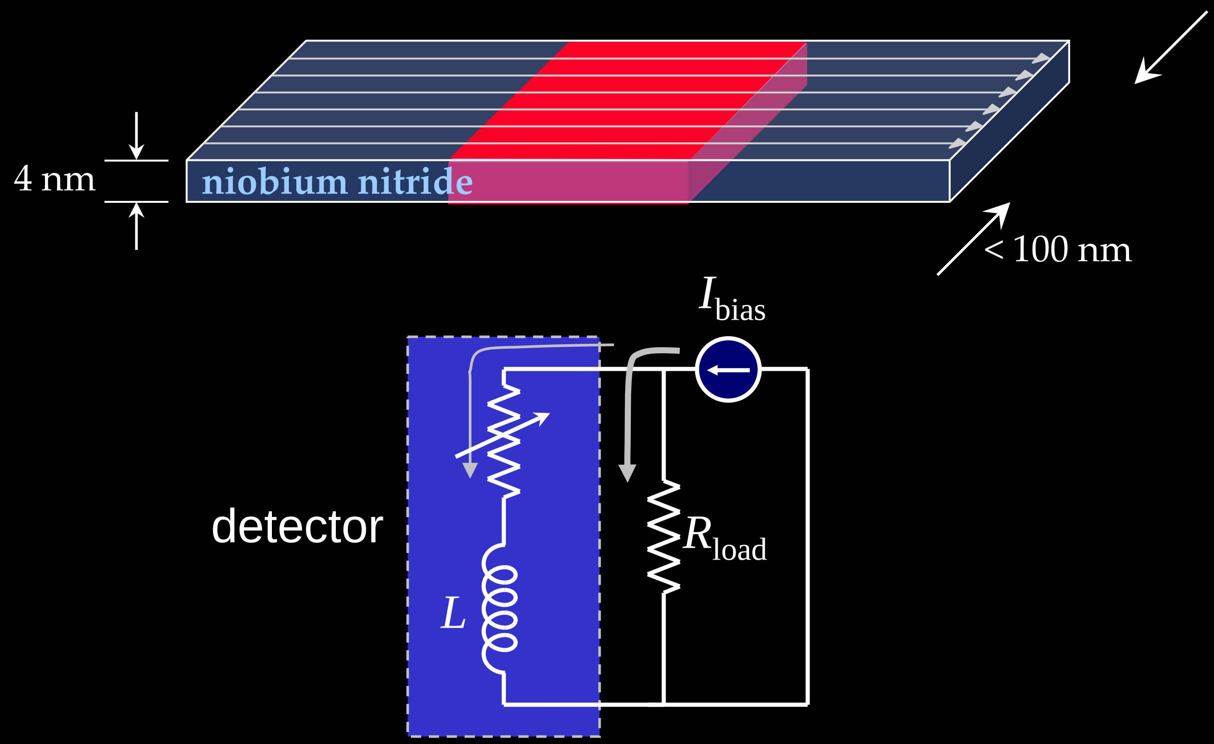
resistive barrier spans nanowire



Acceleration/Heating

Critical Temperature ~ 11 K

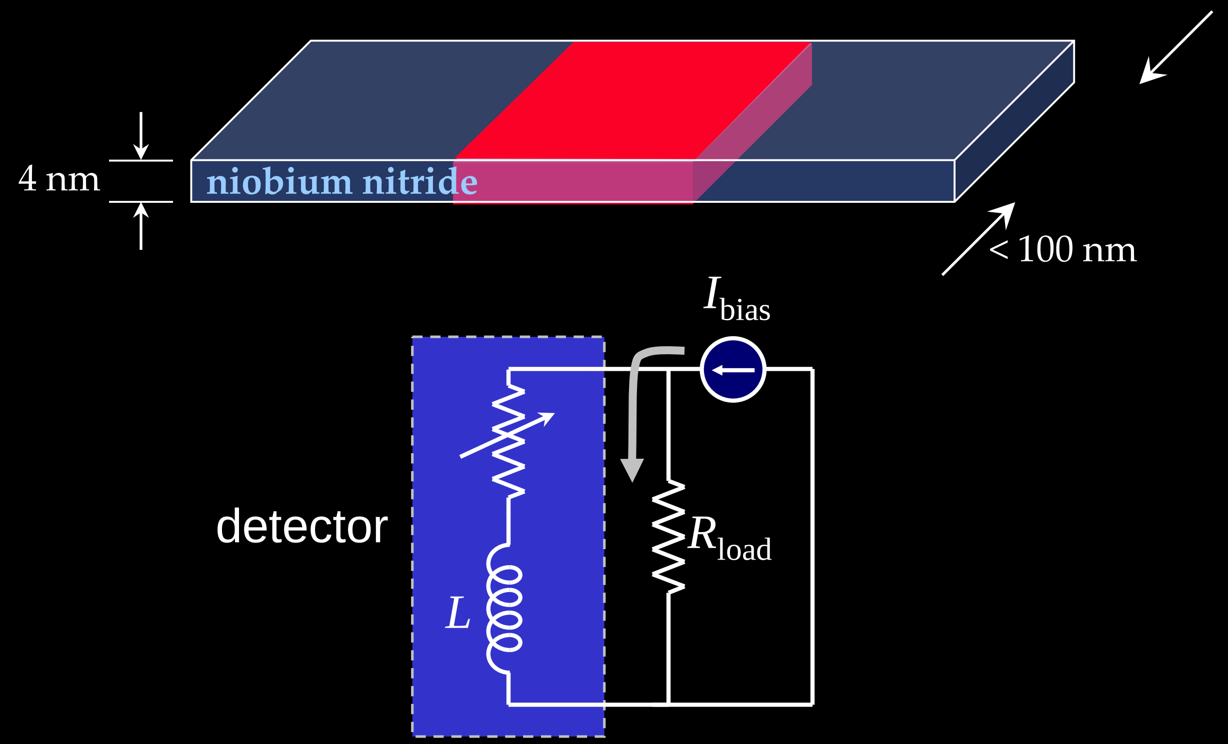
resistance grows from heating



Diversion of Current

Critical Temperature ~ 11 K

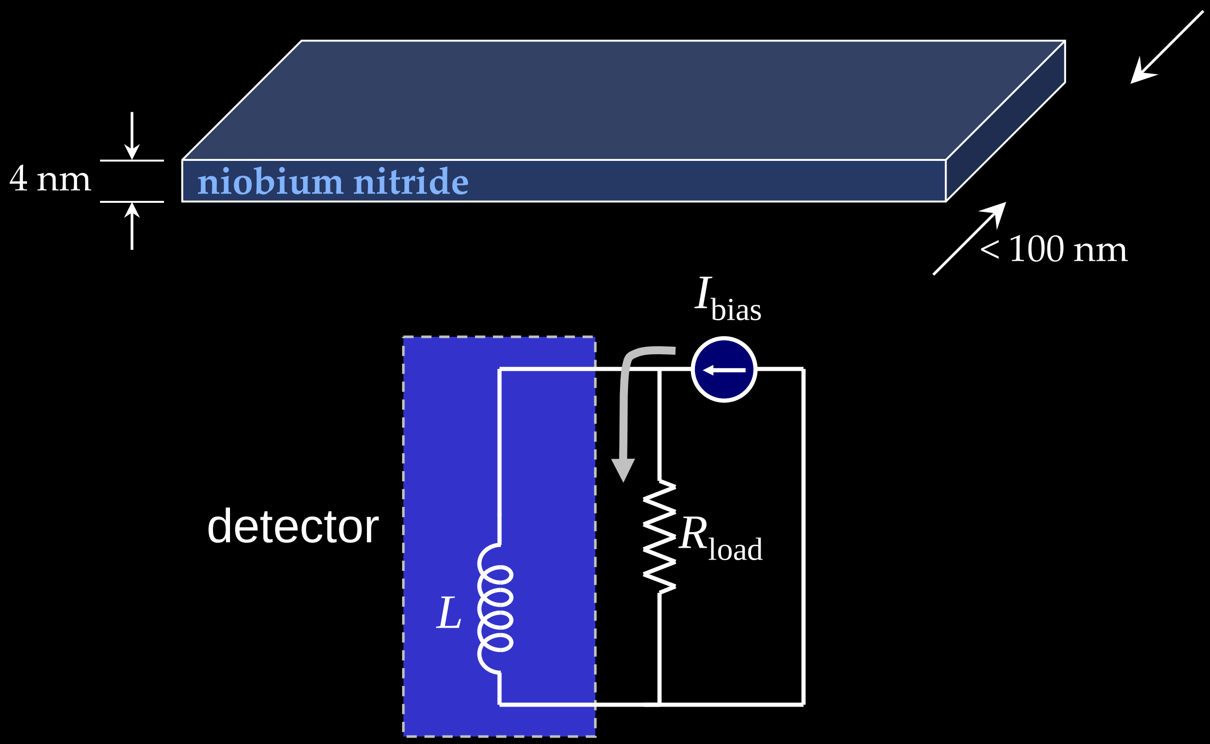
current is diverted



Cooling

Critical Temperature ~ 11 K

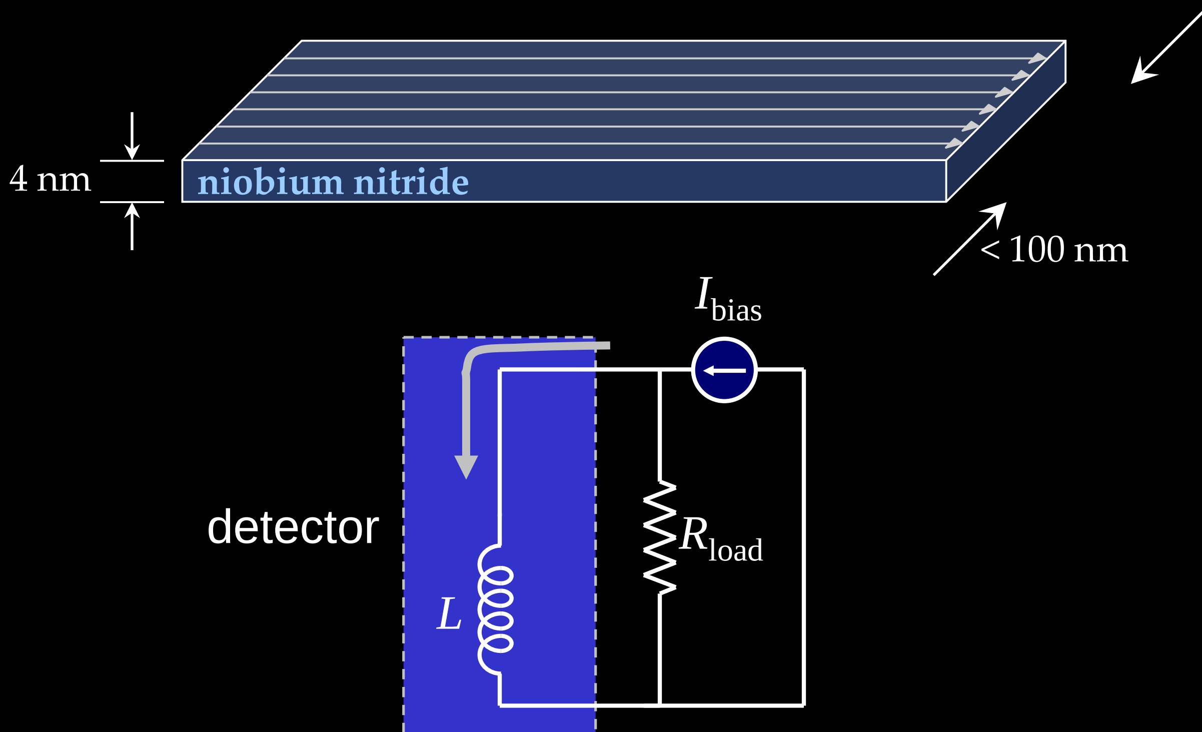
superconductivity is restored



Reset

Critical Temperature ~ 11 K

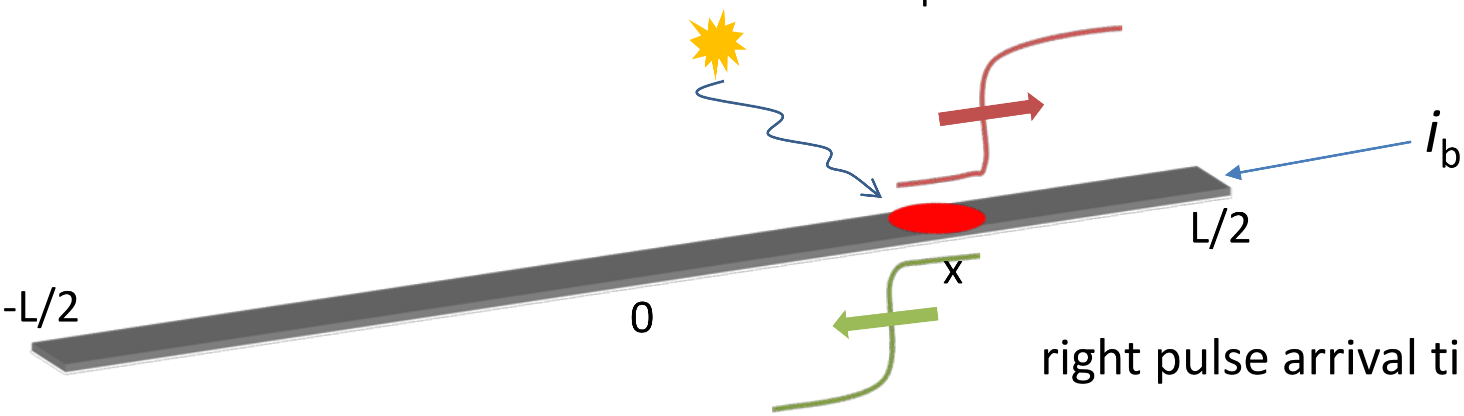
bias current is restored



Kerman, Dauler, Keicher, Yang, KB, Gol'tsman, Voronov, *Applied Physics Letters*, **(2006)**

Spatial and temporal detection in a wire

Photon arrives at x, t_p



right pulse arrival time

$t_R = t_p + (L/2-x)/c'$

left pulse arrival time:

$t_L = t_p + (L/2+x)/c'$

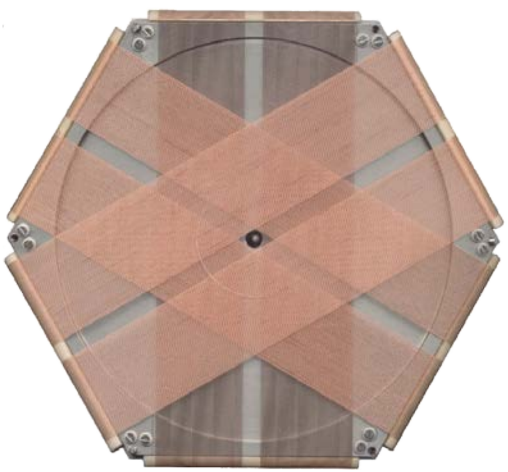
Location: $x = (t_L - t_R)c'/2$ — differential time

Time: $t_p = (t_L + t_R - L/c')/2$ — sum time

Photon position and arrival time can be detected **simultaneously**!

Similar readout architectures in other detector arrays

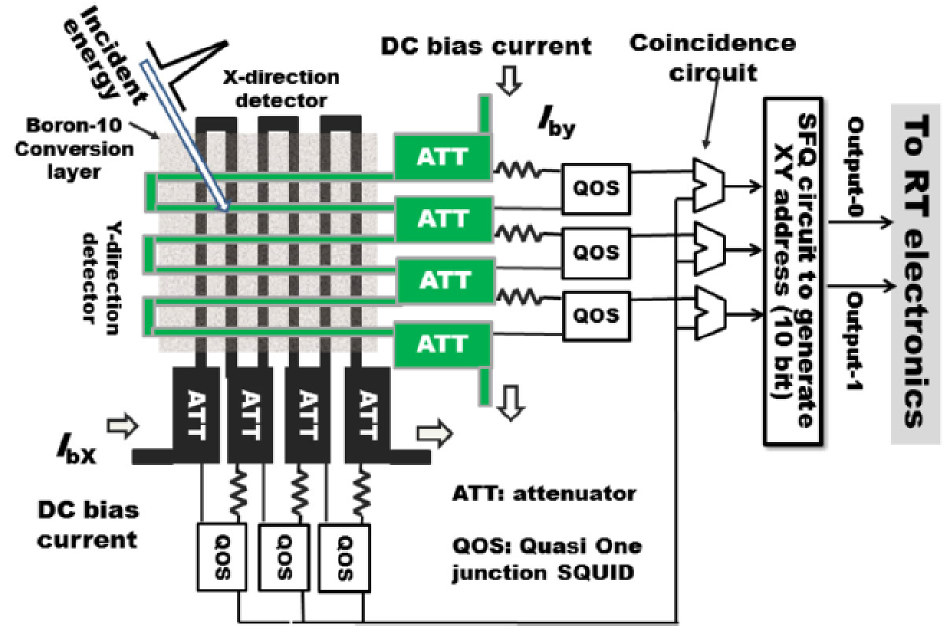
micro-channel plate (MCP) using delay lines for imaging



http://www.roentdek.com/

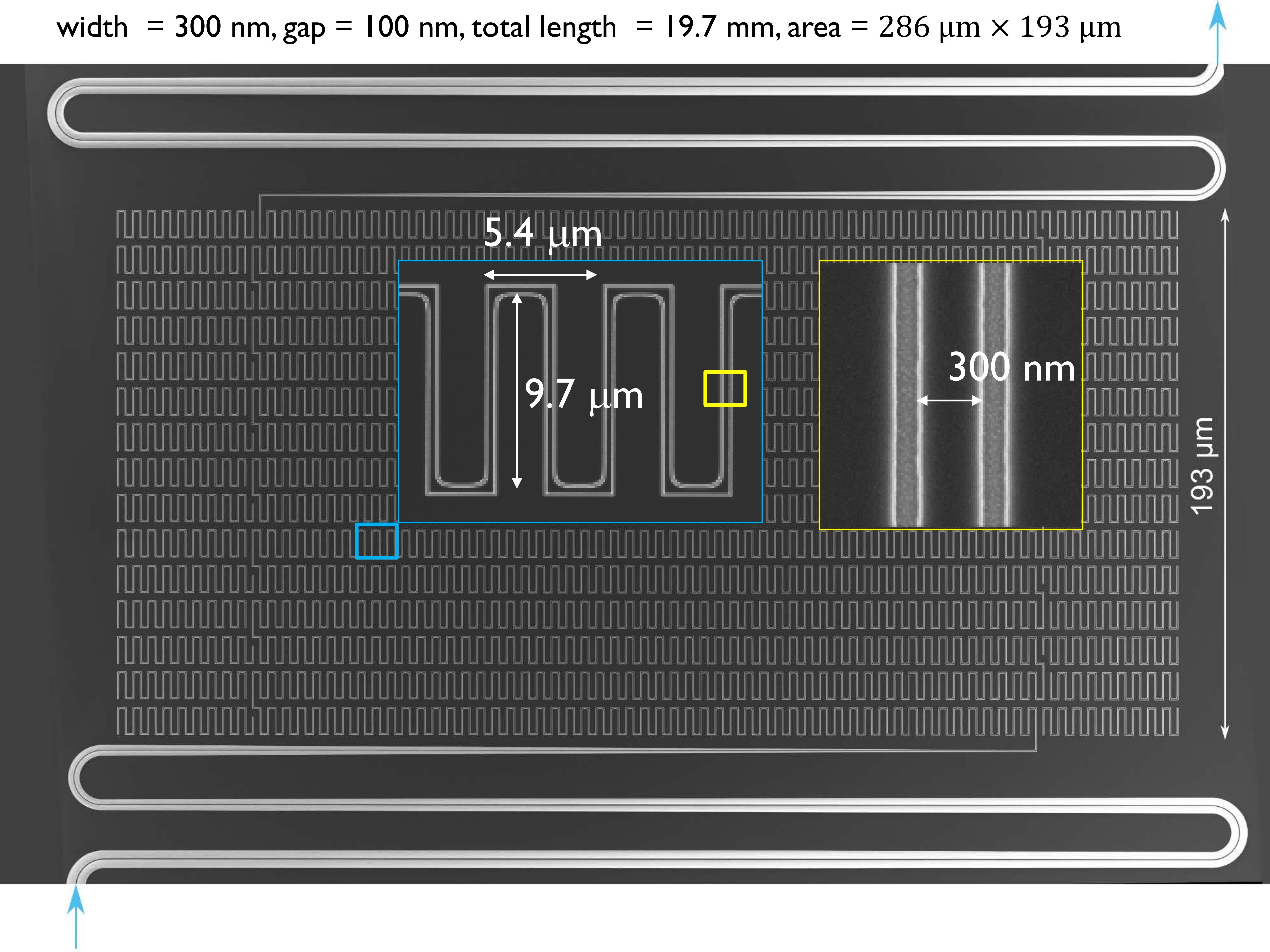
*O. Jagutzki *et al.*, *Nucl. Instruments Methods Phys. Res. Sect. A* **477**, 244–249 (2002)

Neutron imager using delay lines



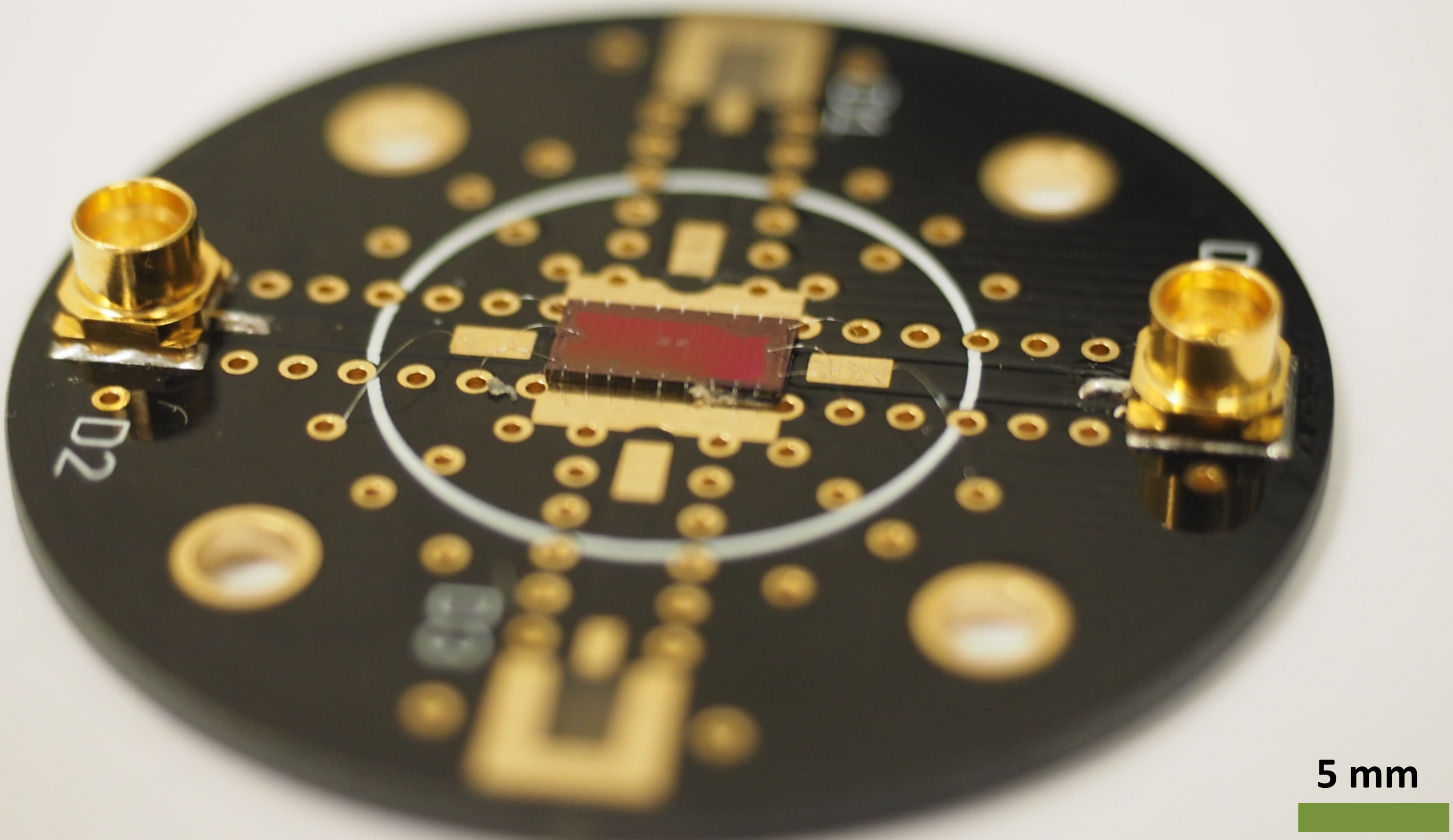
*T. Ishida, *et.al., J. Low Temp. Phys.*, vol. 176, no. 3–4, pp. 216–221, 2014.

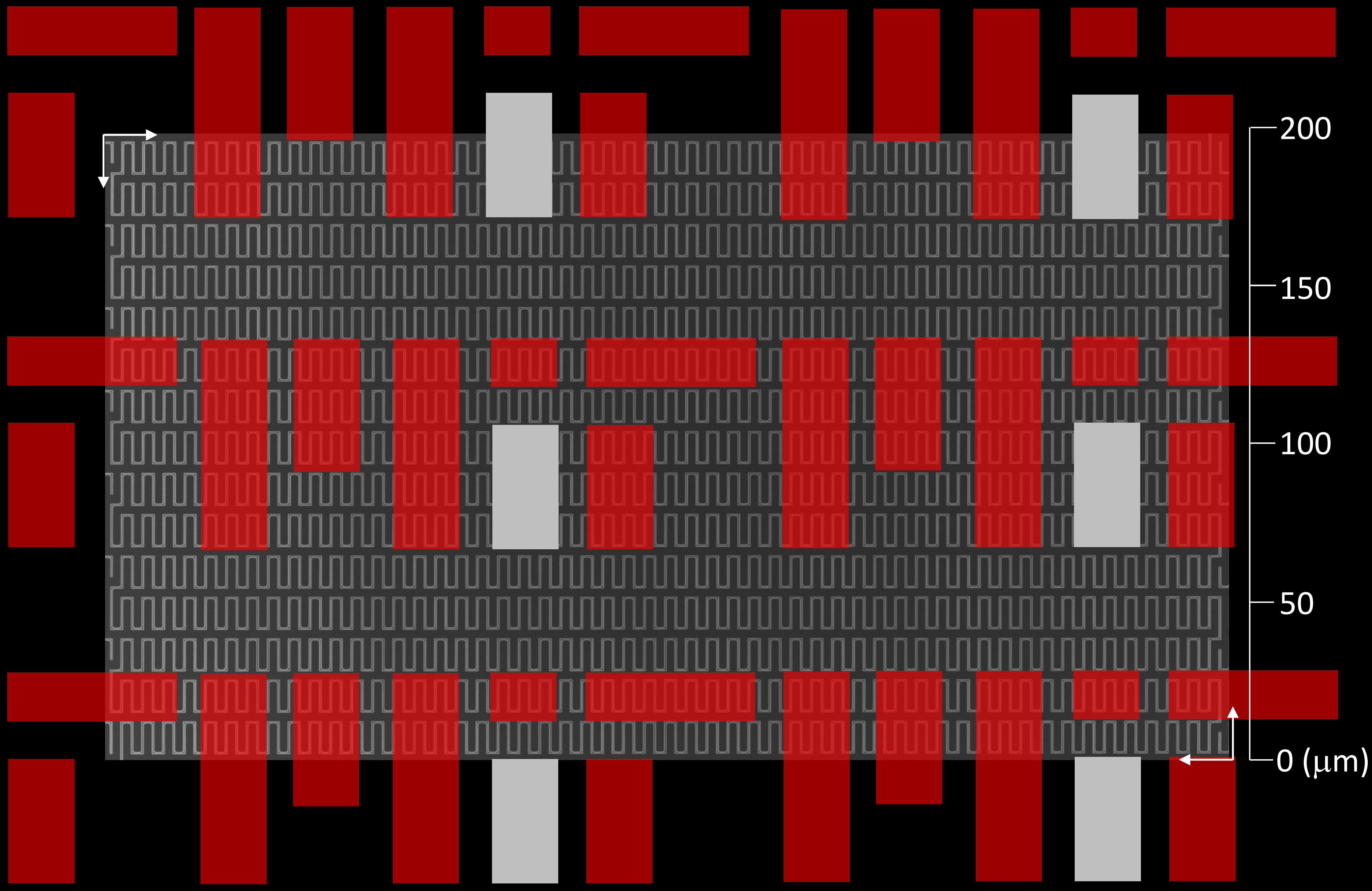
width = 300 nm, gap = 100 nm, total length = 19.7 mm, area = 286 μm × 193 μm



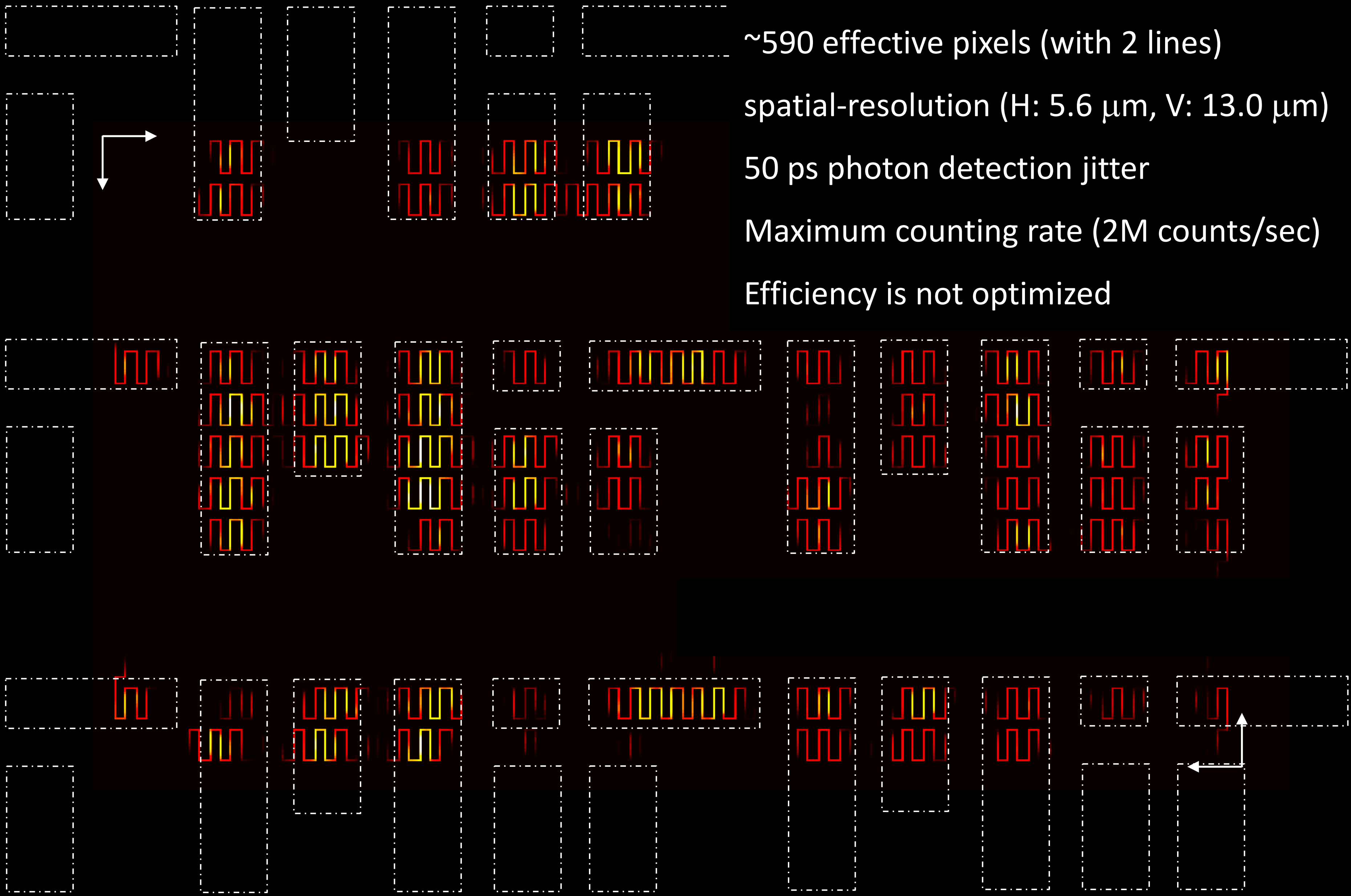
Two connectors for one imager (>500 pixels)

No cryogenic circuit is required




200
150
100
50
0 (μm)

Mapping each photon position to form an image



~590 effective pixels (with 2 lines)

spatial-resolution (H: 5.6 μm, V: 13.0 μm)

50 ps photon detection jitter

Maximum counting rate (2M counts/sec)

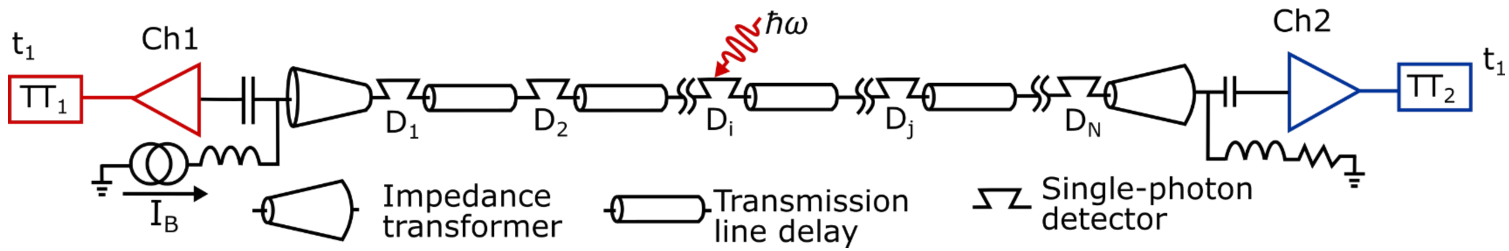
Efficiency is not optimized

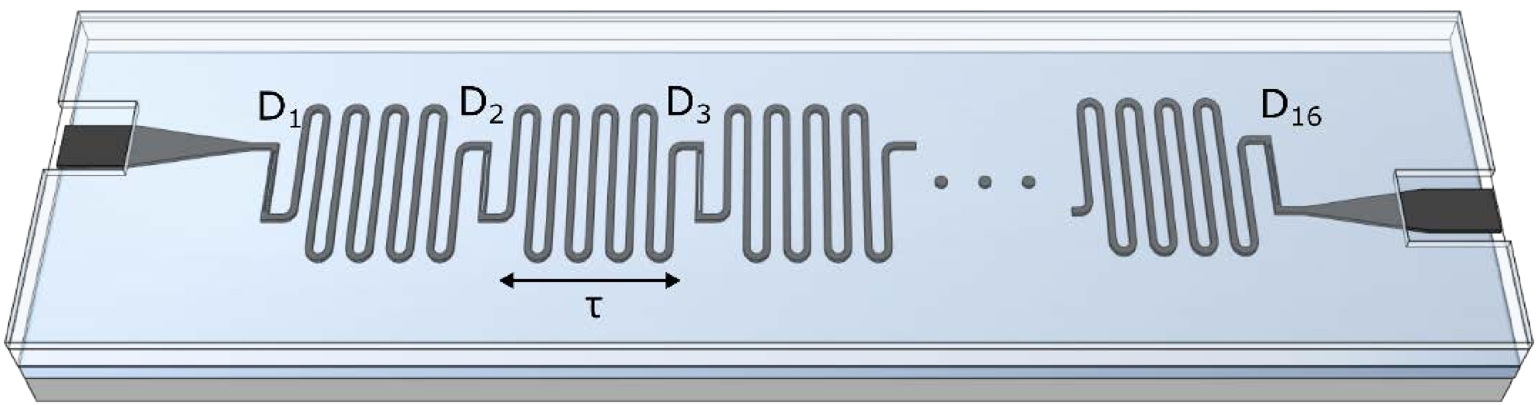
Q.-Y. Zhao, *et.al., "Single-photon imager based on a superconducting nanowire delay line".* Nature Photonics 11 (4), 247-251

Can We Observe Two-Photon Coincidences?

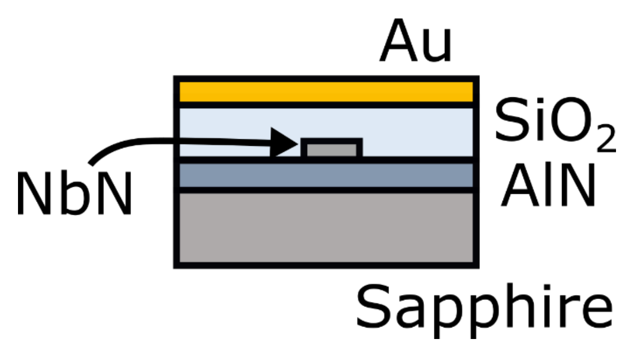
- Assume a pulsed source of photons (not continuous wave sources)
- Assume light will be coupled in via waveguides (not free space)

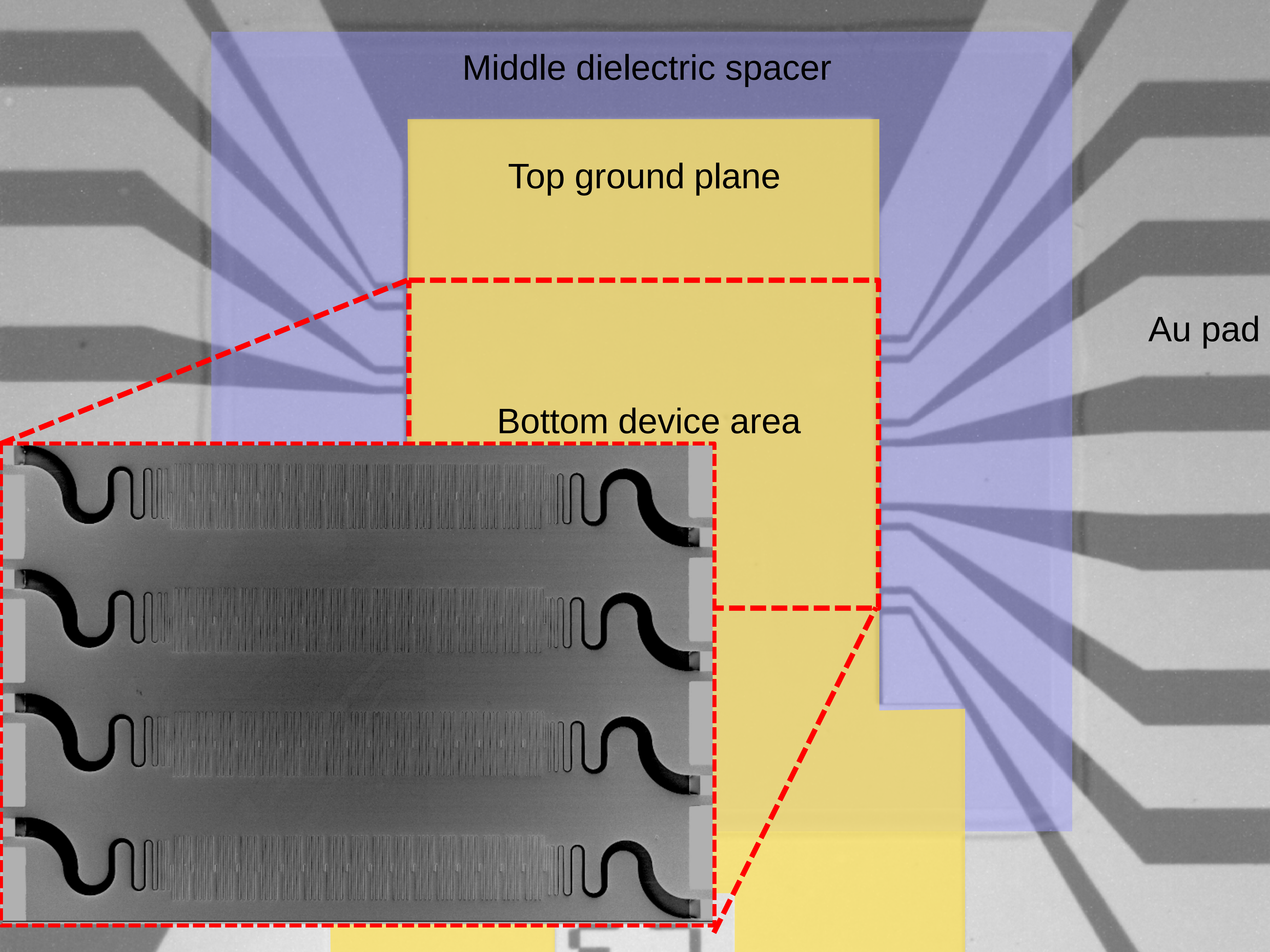
Delay-line Multiplexing



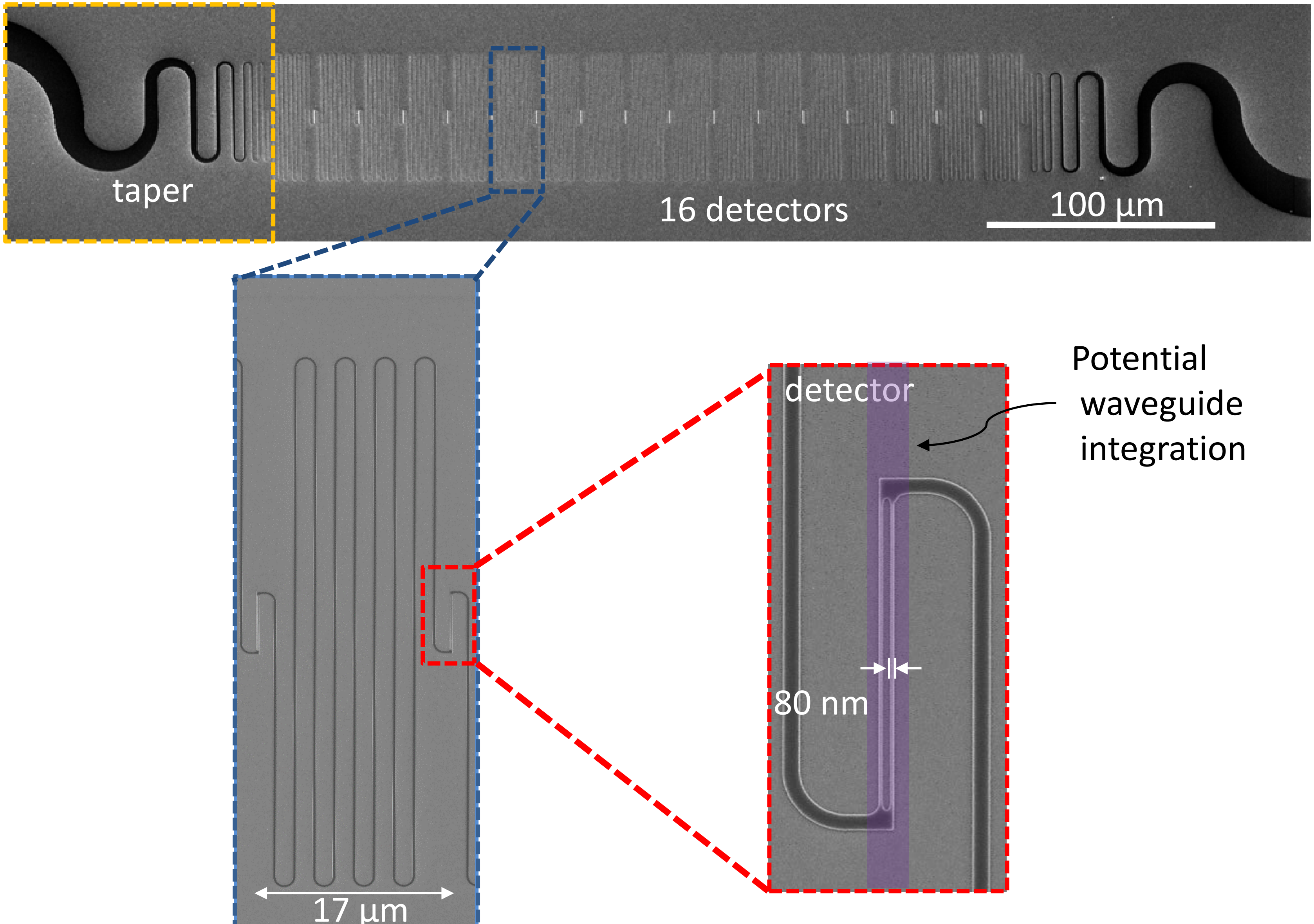


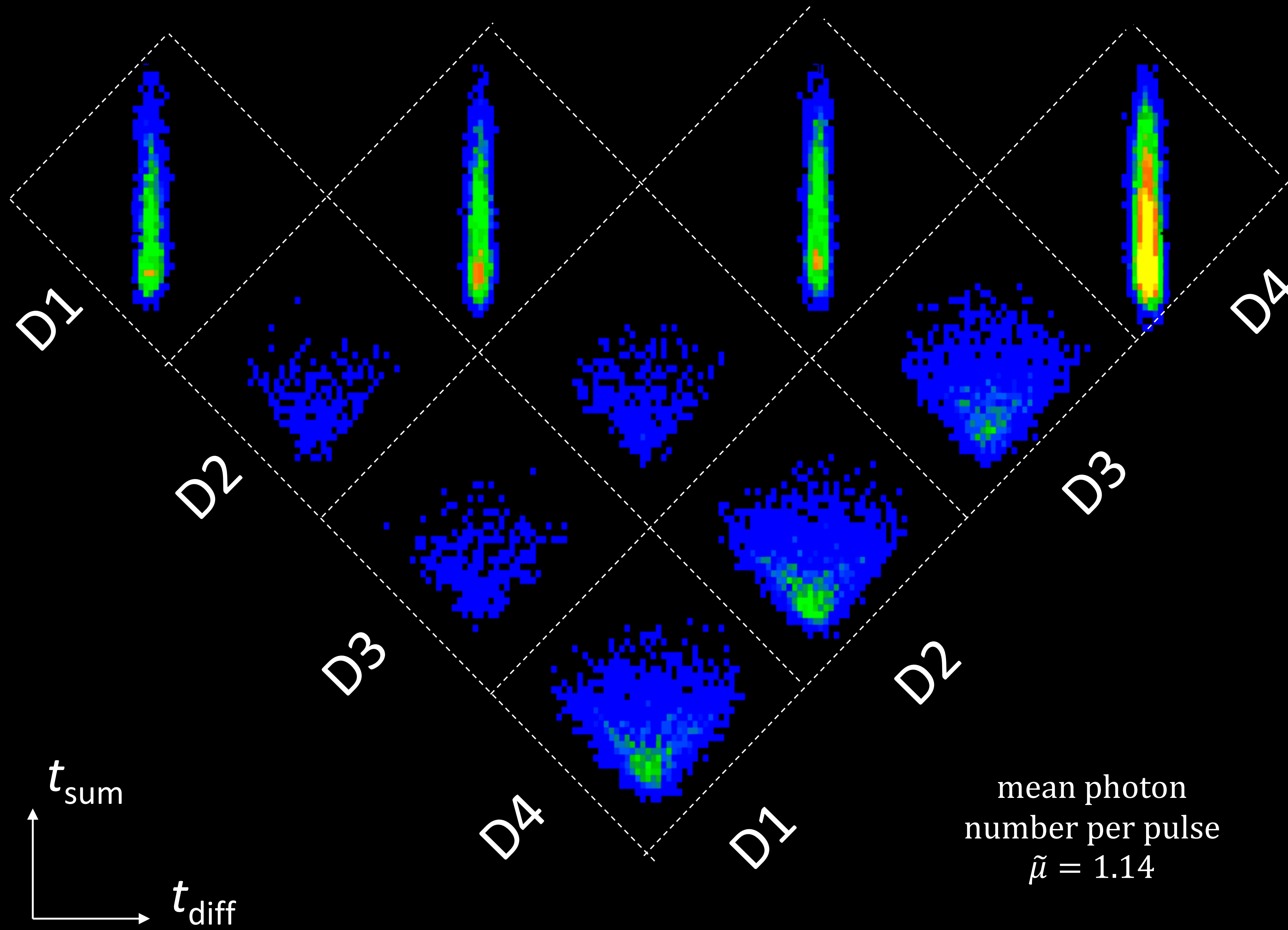
Nanowire microstrip transmission line



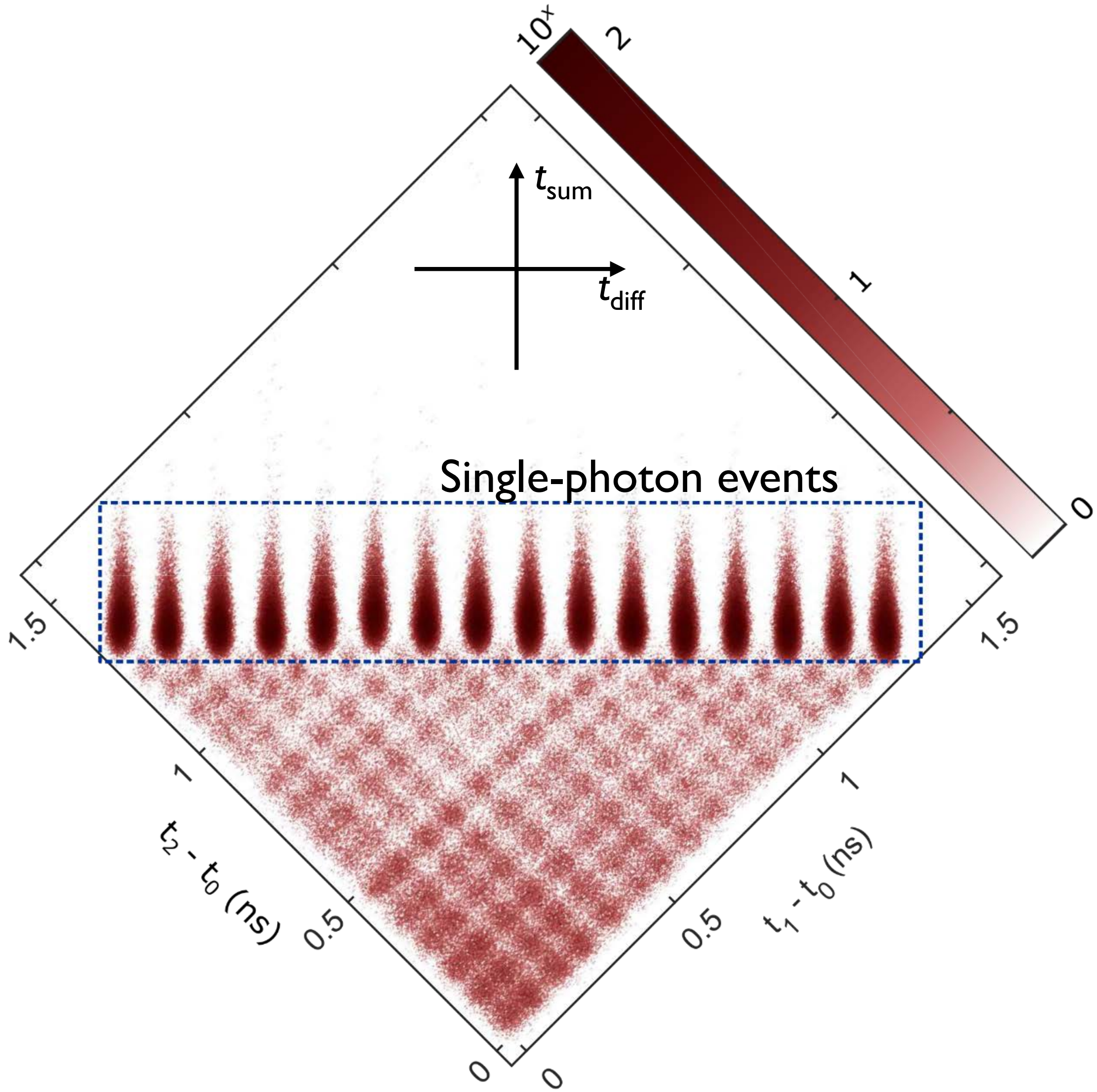

Middle dielectric spacer
Top ground plane
Au pad
Bottom device area

Delay line multiplexing




D1
D2
D3
D4
D1
D2
D3
D4
t_{sum}
t_{diff}
mean photon
number per pulse
$\tilde{\mu} = 1.14$

16-Element-detector chain



D Zhu, *et. al,* CLEO 2017: Applications and Technology, JTh5B. 4

What Have We Learned?

1. SNSPDs provide a unique blend of performance across a wide range of metrics
2. Imaging and time-stamping is enabled by their interesting microwave characteristics

Where Are We Going?

1. Photon-number resolution
2. Large imaging arrays
3. Even-shorter jitter
4. Integration with quantum-limited amplifiers for readout

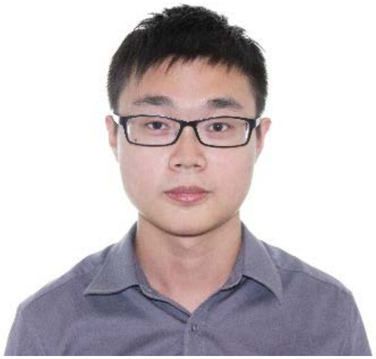
Superconductivity Team in QNN Group

Qing-Yuan Zhao
(Now Prof.,
Nanjing U.)

Andrew Dane
(NASA Fellow)

Reza Baghdadi
(Post-Doc)

Emily Toomey
(NSF Fellow)



Di Zhu
(A*Star Fellow)

Brenden Butters
(Grad Student)

Murat Onen
(Grad Student)

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Niccolo Calandri
Yachin Ivry
Adam McCaughan
Faraz Najafi
Kristen Sunter
Hao-Zhu Wang

SUPPORT

- U.S. Air force Office of Scientific Research
- U.S. Office of Naval Research
- DARPA
- IARPA
- NASA
- NSF
- Many U.S. and international fellowships

Quantum Electron Microscopy

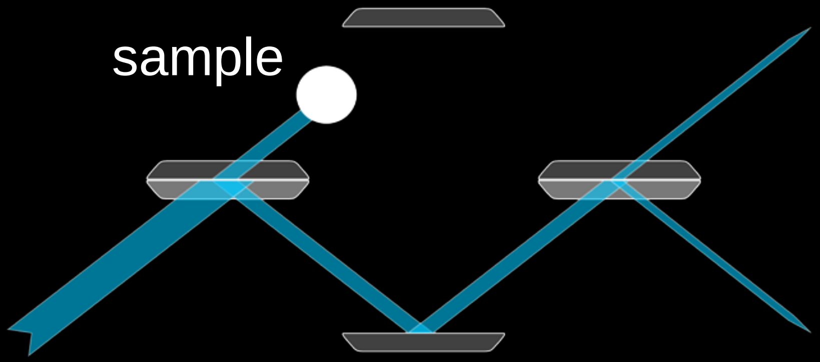
Karl K. Berggren[1], Dept. of EECS

Chung-Soo Kim[1], Richard G. Hobbs[1], Yujia Yang[1], Vitor R. Manfrinato[1], Orhan Celiker[1], Navid Abedzadeh[1], Akshay Agarwal[1], Wenping Li[1], Qingyuan Zhao[1], Corey Cleveland[1], Marco Turchetti[1], Mehmet F. Yanik[1] and Pieter Kruit[2]

[1]Massachusetts Institute of Technology
[2]Delft University of Technology

Interaction-Free Measurement (with Photons)

beam
splitter



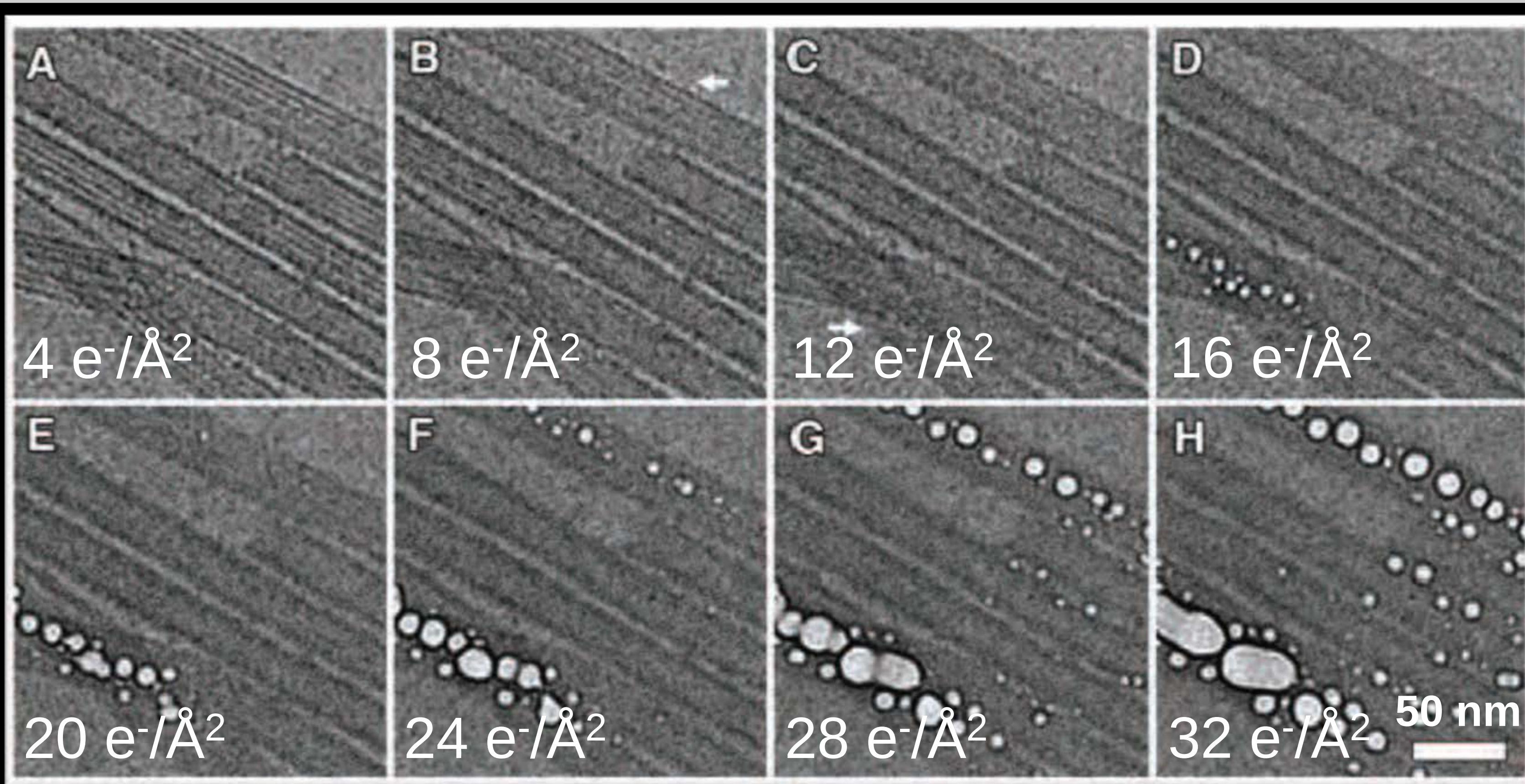
beam

mirror

A. C. Elitzur & L. Vaidman “Quantum mechanical interaction-free measurements” *Found. Phys.*, **1993**, *23*, 987

Interaction-free measurement success probability: 25%

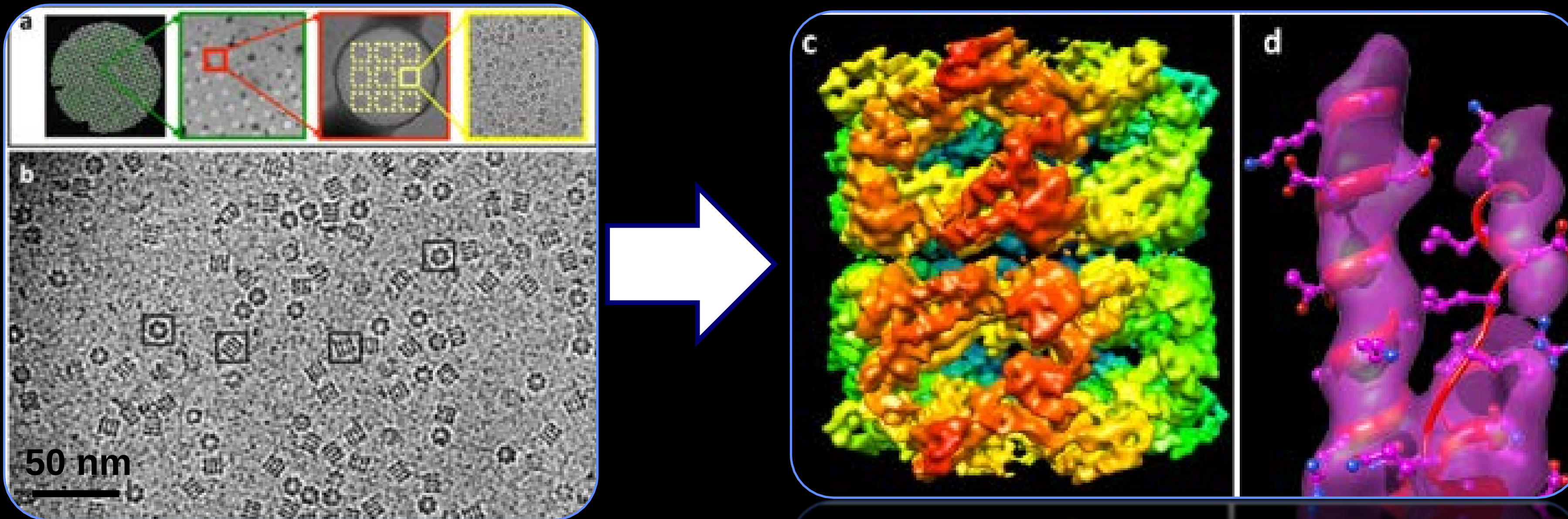
Electron-Beam Induced Damage



Carlson, D. B.; Evans, J. E. Low-Dose Imaging Techniques for Transmission Electron Microscopy. In The Transmission Electron Microscope; Khan, M., Ed.; Intech, 2012.

Grubb and Keller (1972) - Irradiation received by the specimen during a single recording equivalent to a 10 megaton hydrogen bomb exploding at a distance of 30 meters away

Cryo-Electron Microscopy



Structural determination of GroEL protein complexes : Milne et al., FEBS J. 2013 January; 280 (1): 28-45

- 2-D projections of particles used to construct 3-D image which is then fitted to existing atomic model; resolution of up to 3 Å achieved
- Susceptible to particle inhomogeneity and chemical non-uniformity; requires many identical particles for averaging; sample still frozen!

Interaction-Free Measurement (with Electrons)

RAPID COMMUNICATIONS

PHYSICAL REVIEW A **80**, 040902(R) (2009)

Noninvasive electron microscopy with interaction-free quantum measurements

William P. Putnam and Mehmet Fatih Yanik*

Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 20 January 2009; published 23 October 2009)

We propose the use of interaction-free quantum measurements with electrons to eliminate sample damage in electron microscopy. This might allow noninvasive molecular-resolution imaging. We show the possibility of such measurements in the presence of experimentally measured quantum decoherence rates and using a scheme based on existing charged particle trapping techniques.

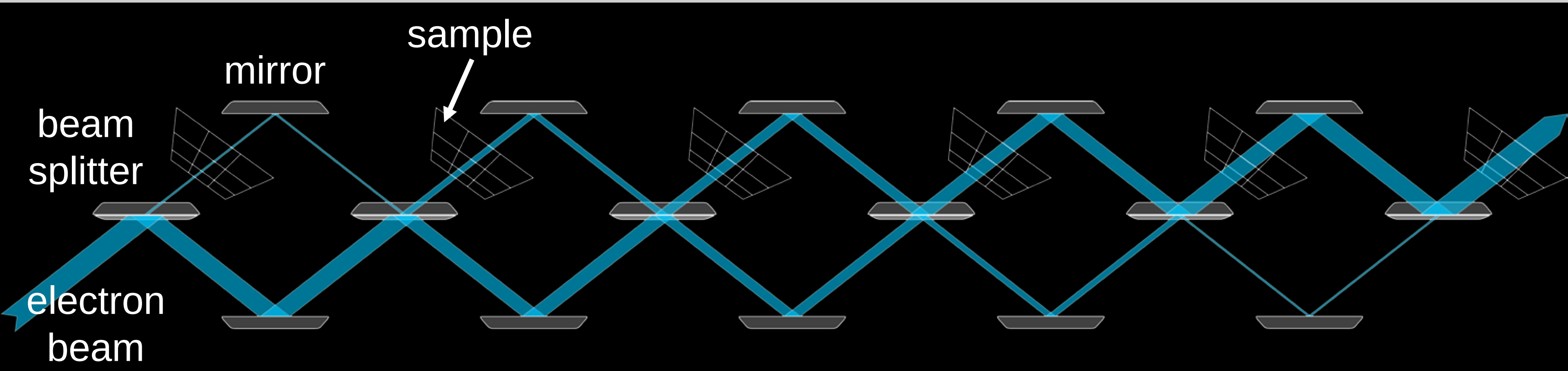
DOI: 10.1103/PhysRevA.80.040902 PACS number(s): 07.78.+s, 42.50.Dv

Electron microscopy has significantly impacted many areas of science and engineering due to its unprecedented atomic and molecular resolution. Yet, the imaging of biological and other sensitive specimens has been limited because

Imagine an electron propagating around the rings. The electron wave function can be separated into an angular θ-dependent portion and a planar (r, z)-dependent part. Due to the double-well potential, the two lowest-energy states of

Putnam & Yanik proposed interaction-free measurement with electrons for electron microscopy

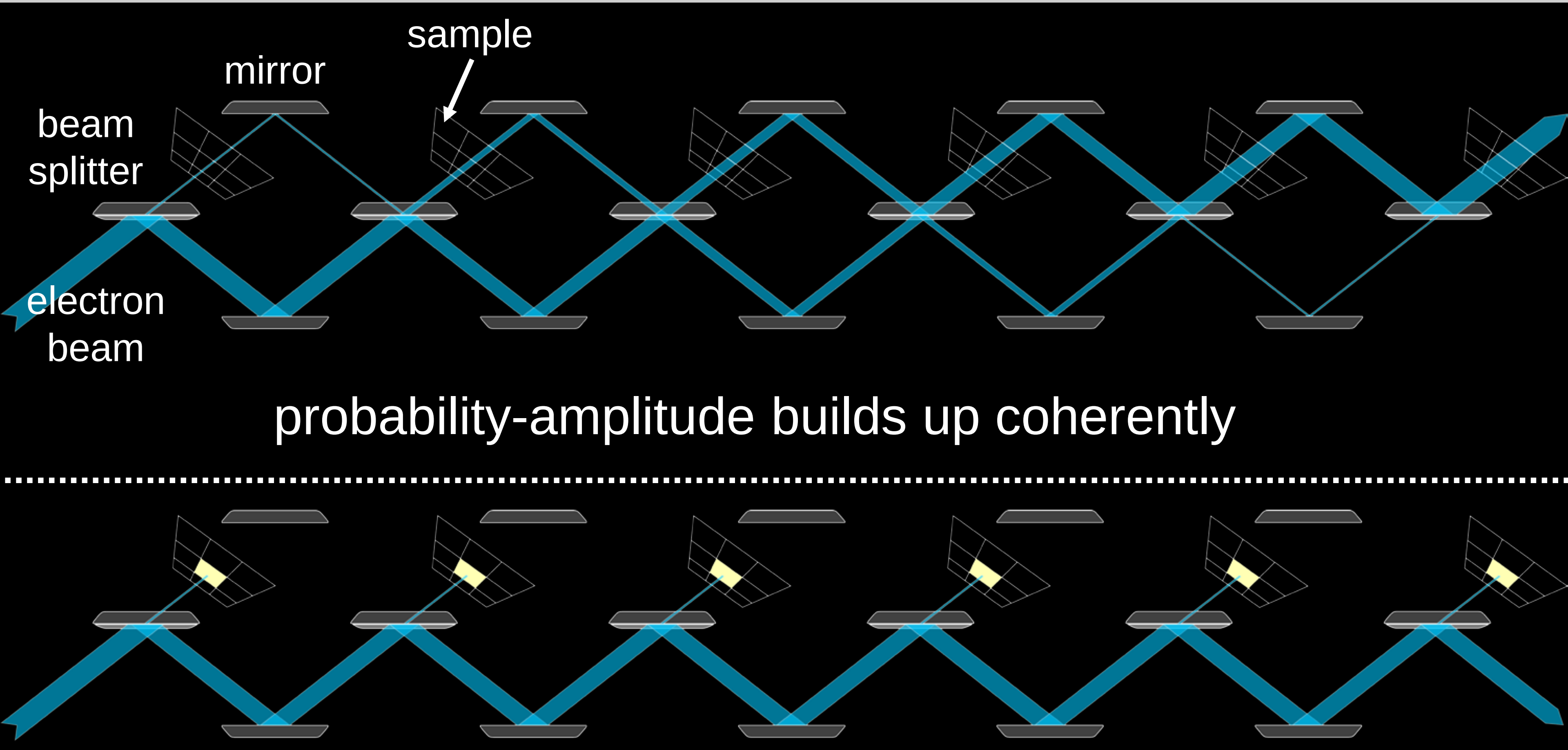
Interaction-Free Measurement



probability-amplitude builds up coherently (~ quadratic)

Kwiat, P. *et al*. *Phys. Rev. Lett.* **1995**, *74*, 4763–4766.

Interaction-Free Measurement

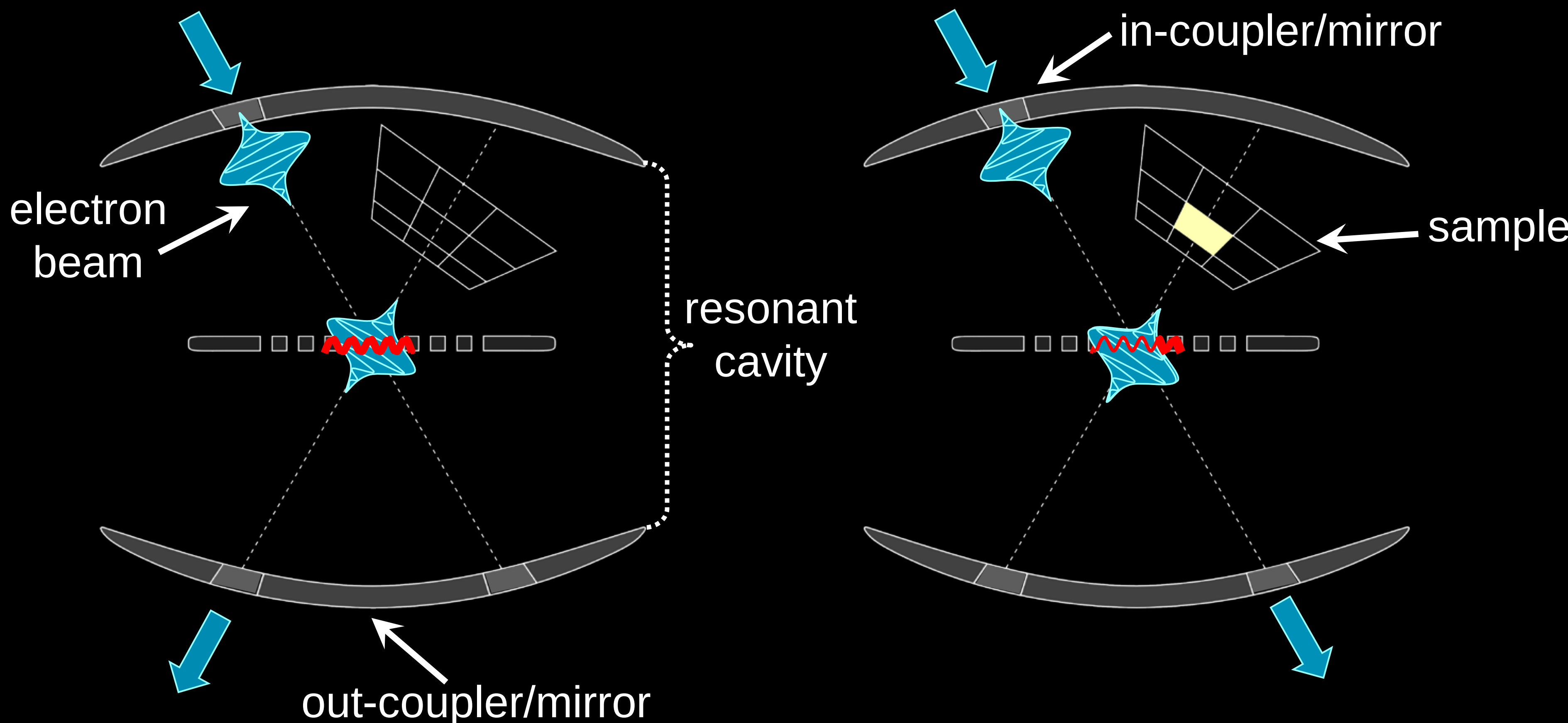


probability-amplitude builds up coherently

probability-amplitude loss to sample builds up only linearly

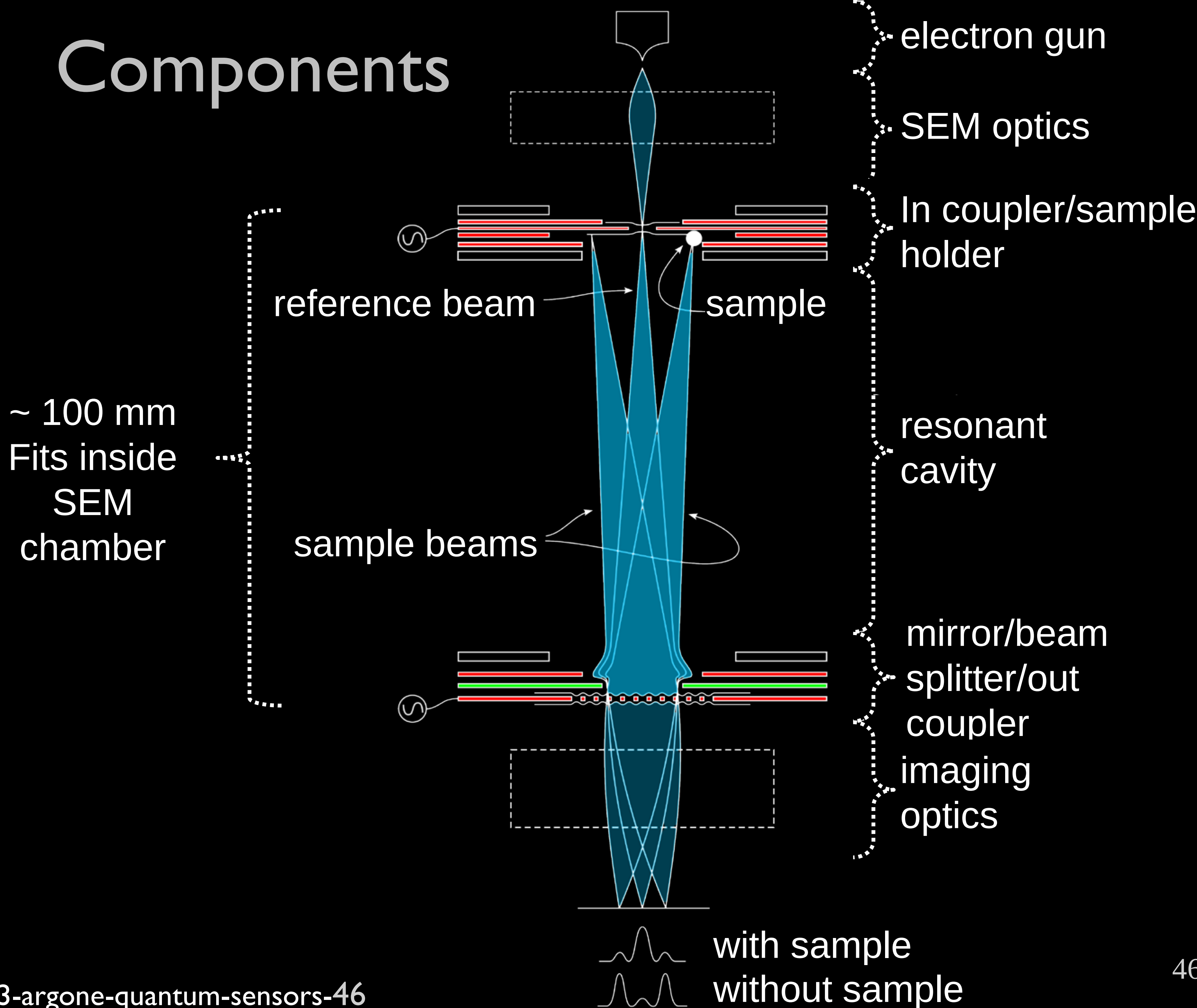
Kwiat, P. *et al*. *Phys. Rev. Lett.* **1995**, *74*, 4763–4766.

Efficient Interaction-Free Measurement



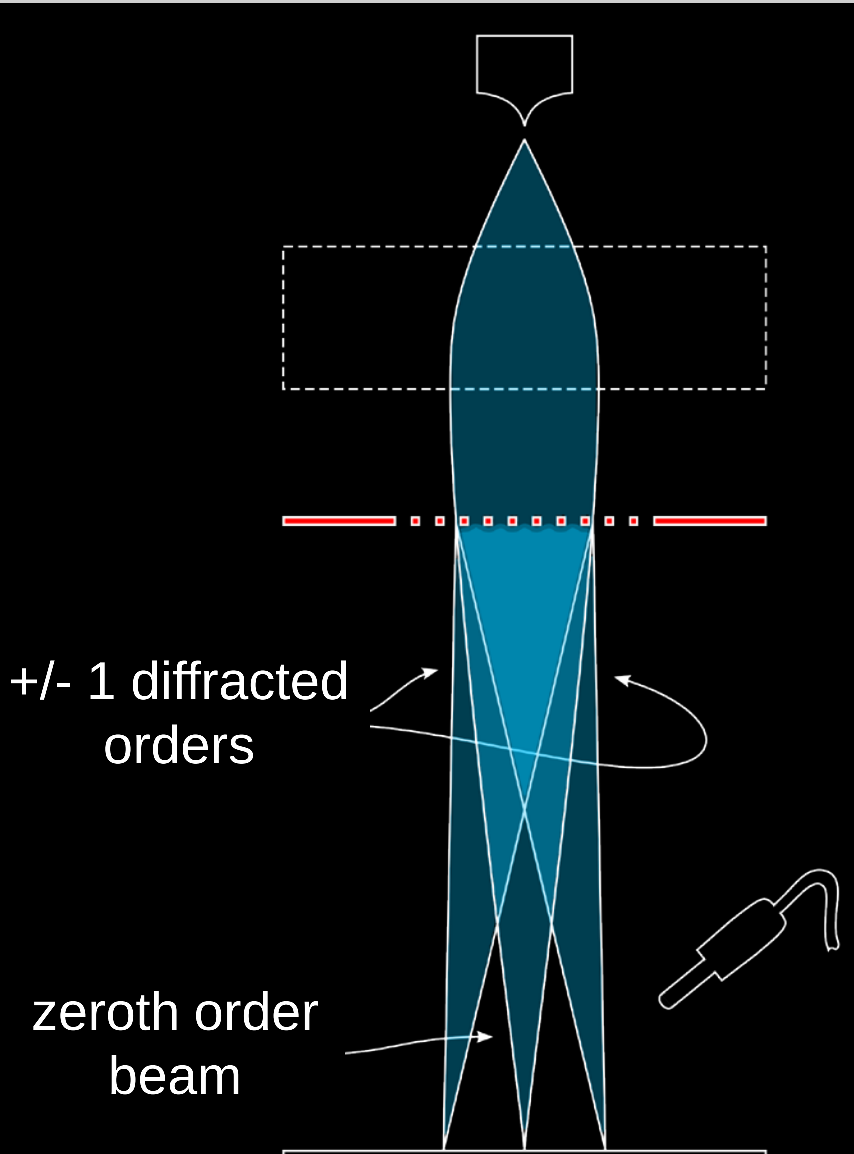
P. Kruit, R.G. Hobbs, C-S. Kim, Y. Yang, V.R. Manfrinato, J. Hammer, S. Thomas, P. Weber, B. Klopfer, C. Kohstall, T. Juffmann, M.A. Kasevich, P. Hommelhoff, K.K. Berggren. "Designs for a quantum electron microscope." Ultramicroscopy 164, 31-45 (2016)

Components



electron gun
SEM optics
In coupler/sample holder
reference beam
sample
~ 100 mm
Fits inside
SEM
chamber
resonant cavity
sample beams
mirror/beam splitter/out coupler
imaging optics
with sample
without sample

Characterization of Beam Splitter



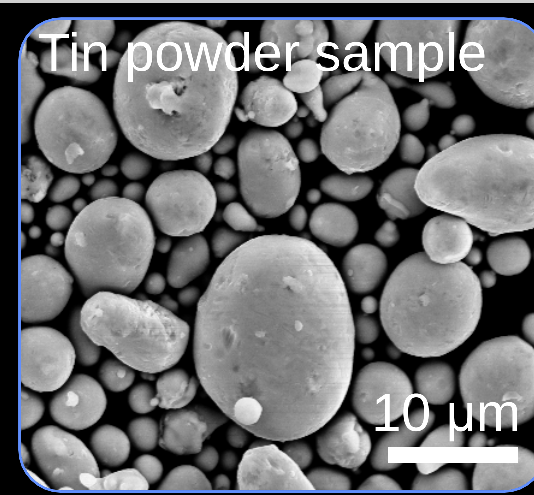
field emission electron gun

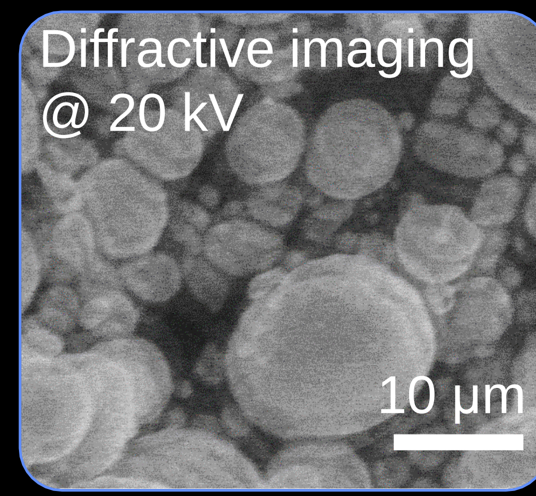
SEM optics

Beam splitter – nanofabricated diffraction grating

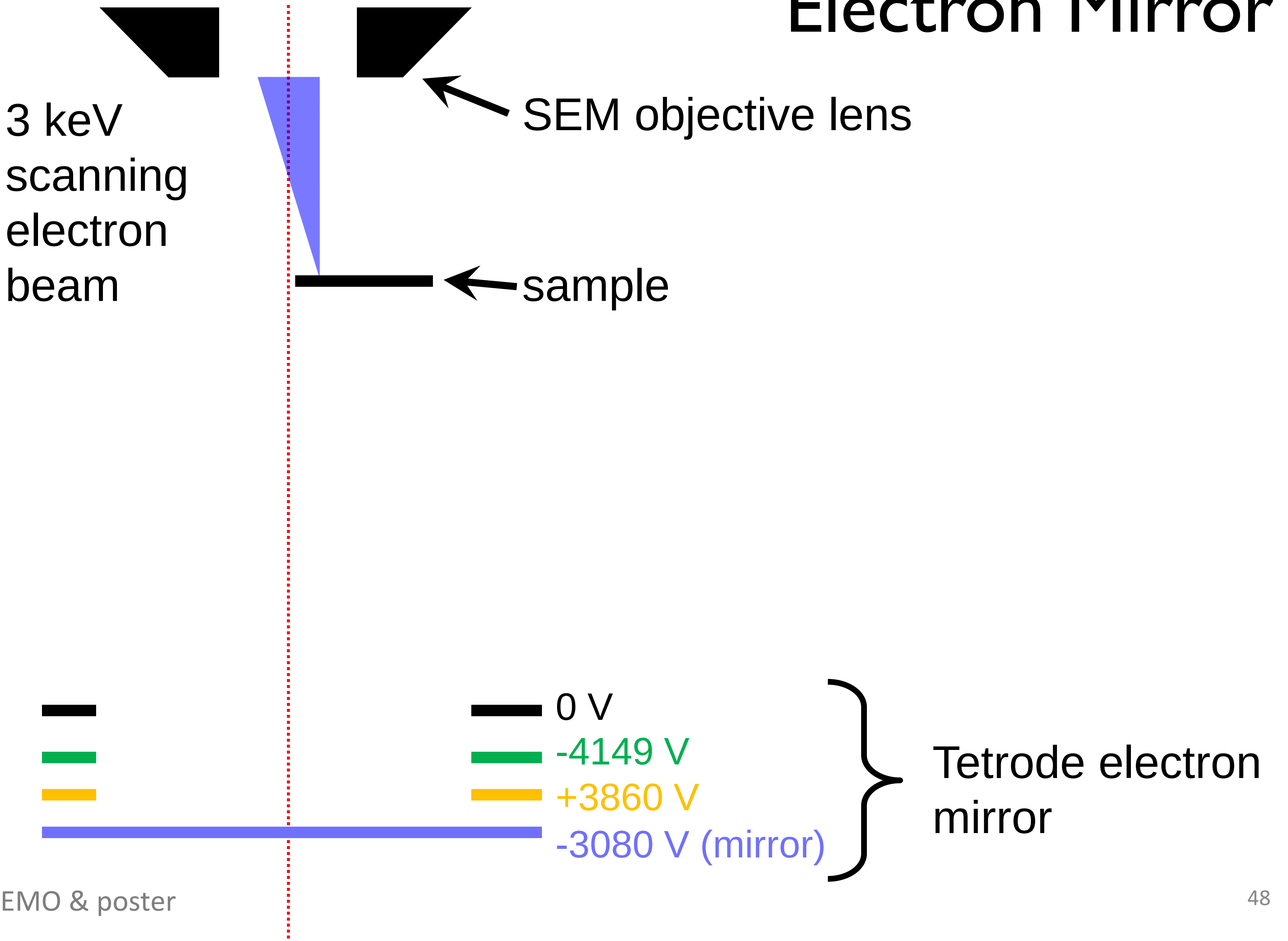
secondary electron detector (Everhart-Thornley)

sample (tin particles)

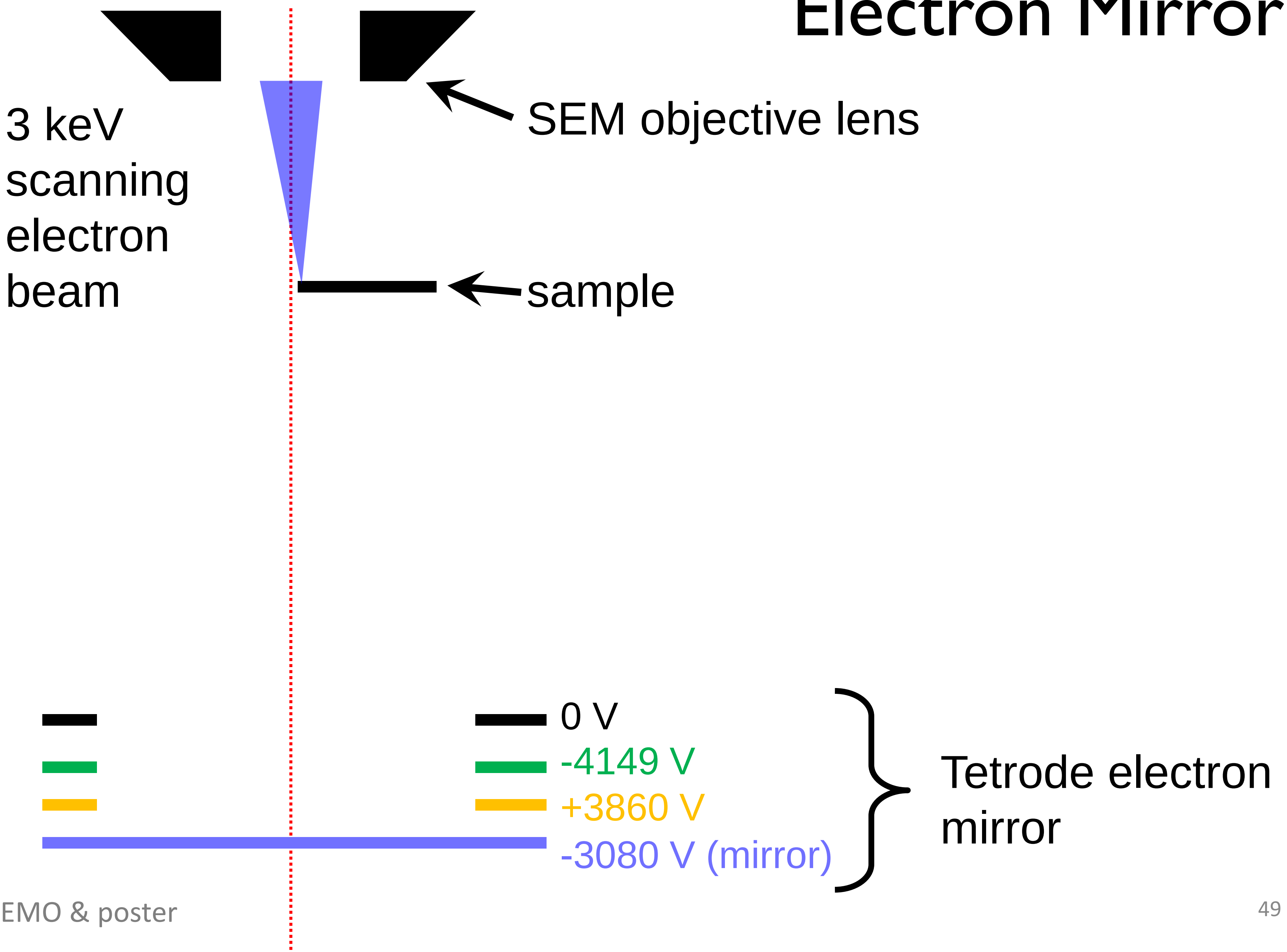




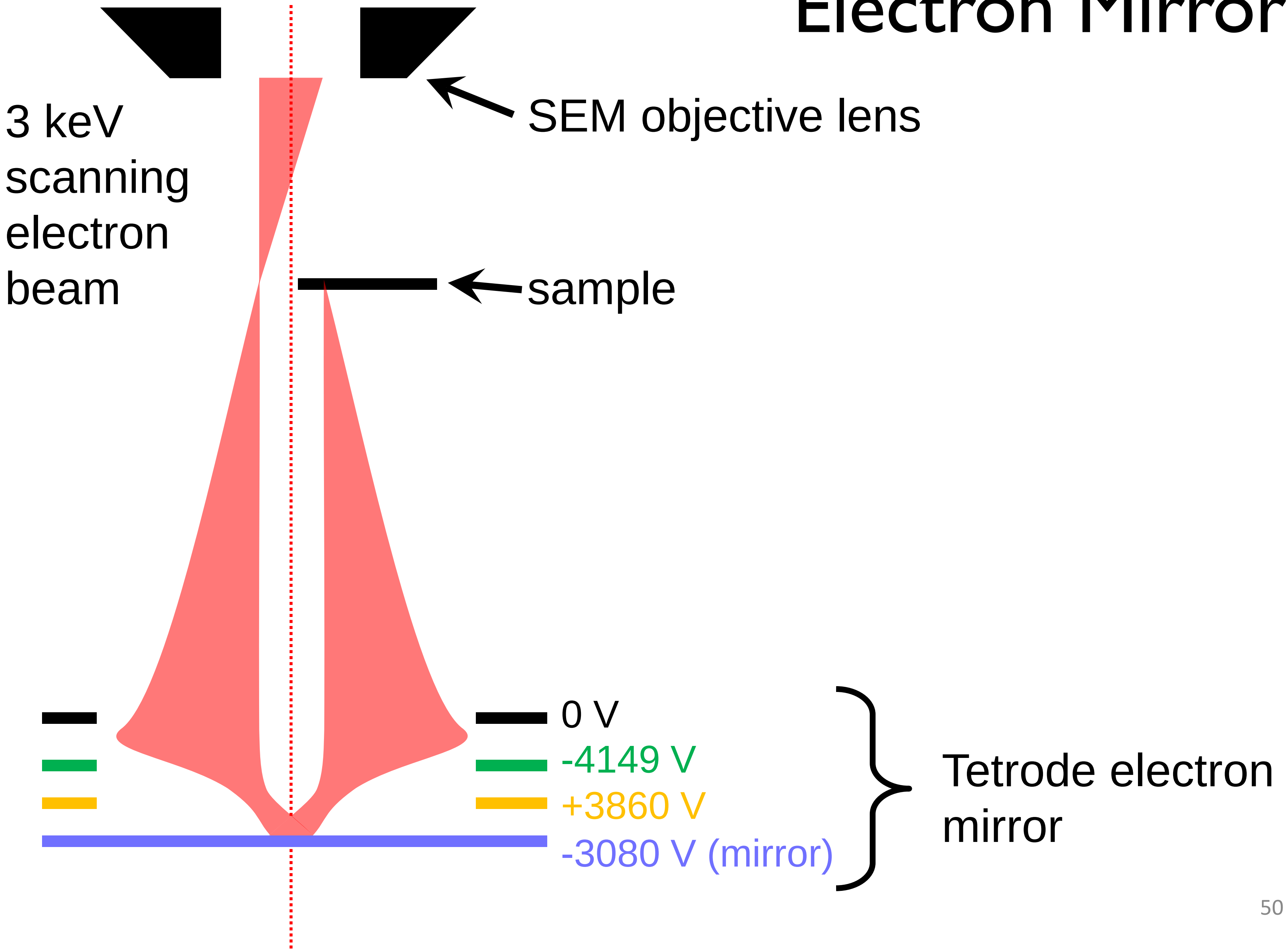
Electron Mirror



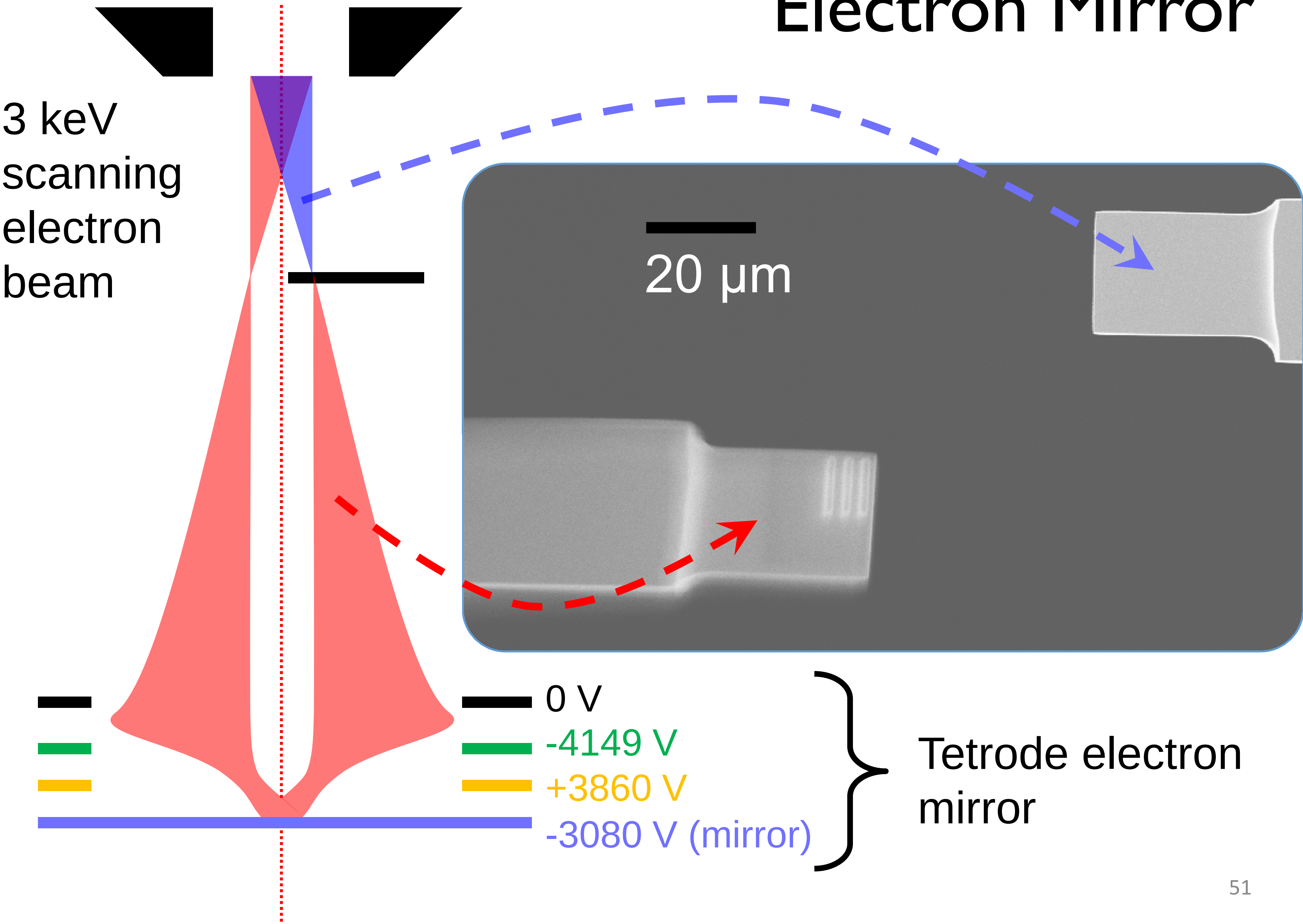
Electron Mirror



Electron Mirror



Electron Mirror



Challenges & Goals for QEM Cavity

Electron optics

- Aberrations propagate for multiple circulations
- Loss in beamsplitter
- Coherence loss in couplers

Imaging

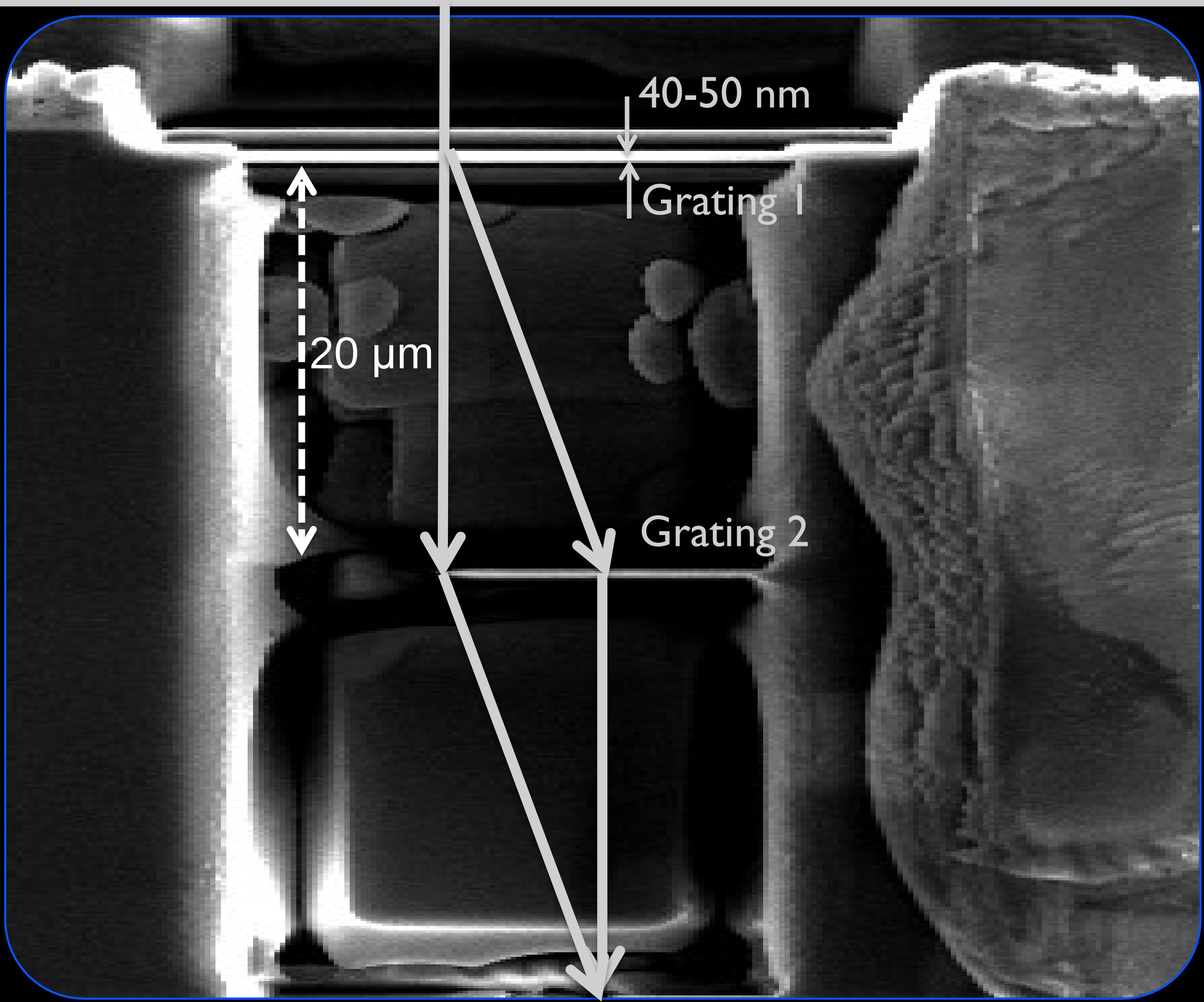
- QEM supports only binary black & white imaging

S. Thomas *et al.*, *Phys. Rev. A* **2014**, 90, 053840.

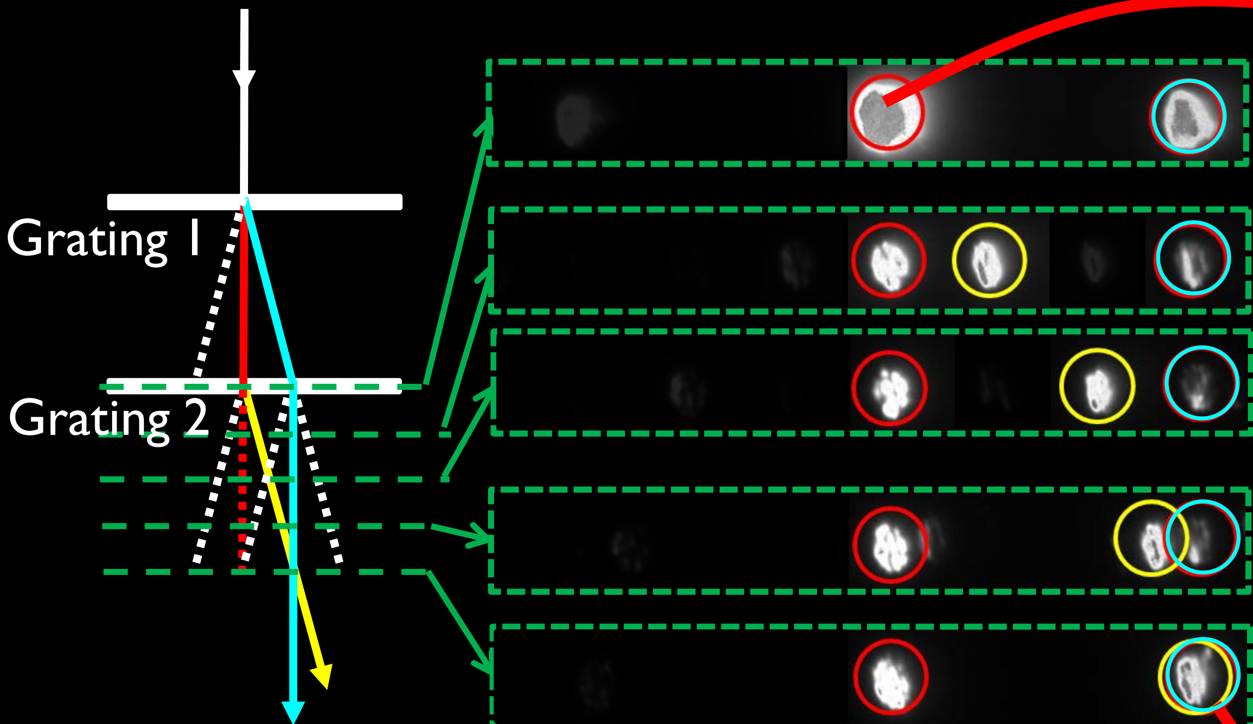
Interaction-free imaging with electrons

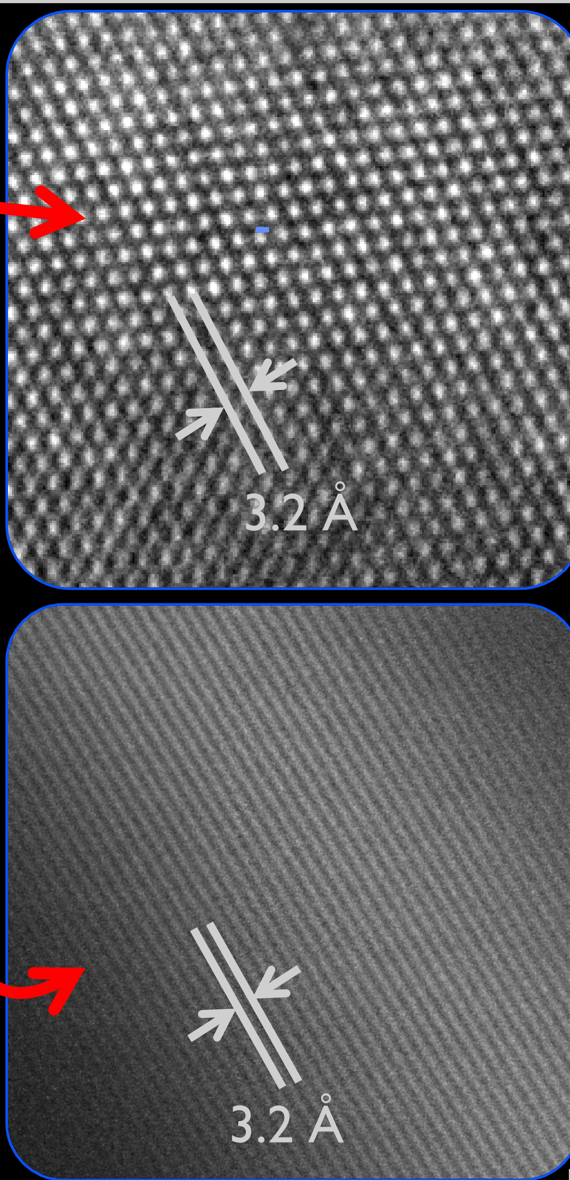
- Requires Mach-Zehnder interferometer

Nano Mach-Zehnder for Electrons



MZ Interferometry with Electrons

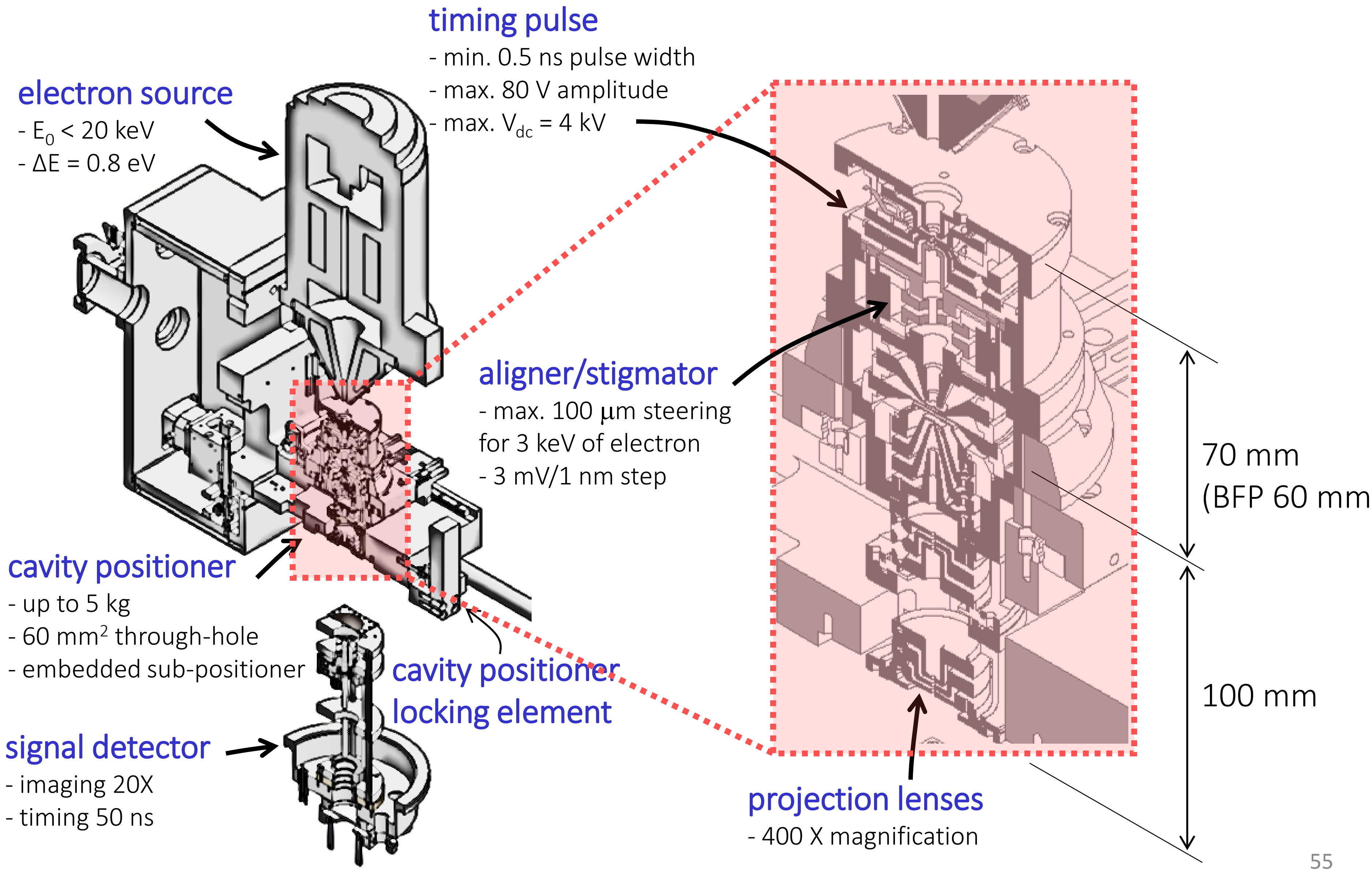




Akshay Agarwal, et. al. "A nanofabricated, monolithic, path-separated electron interferometer." *Scientific Reports 7*. May 2017. With Dirk Van Dyck

See poster

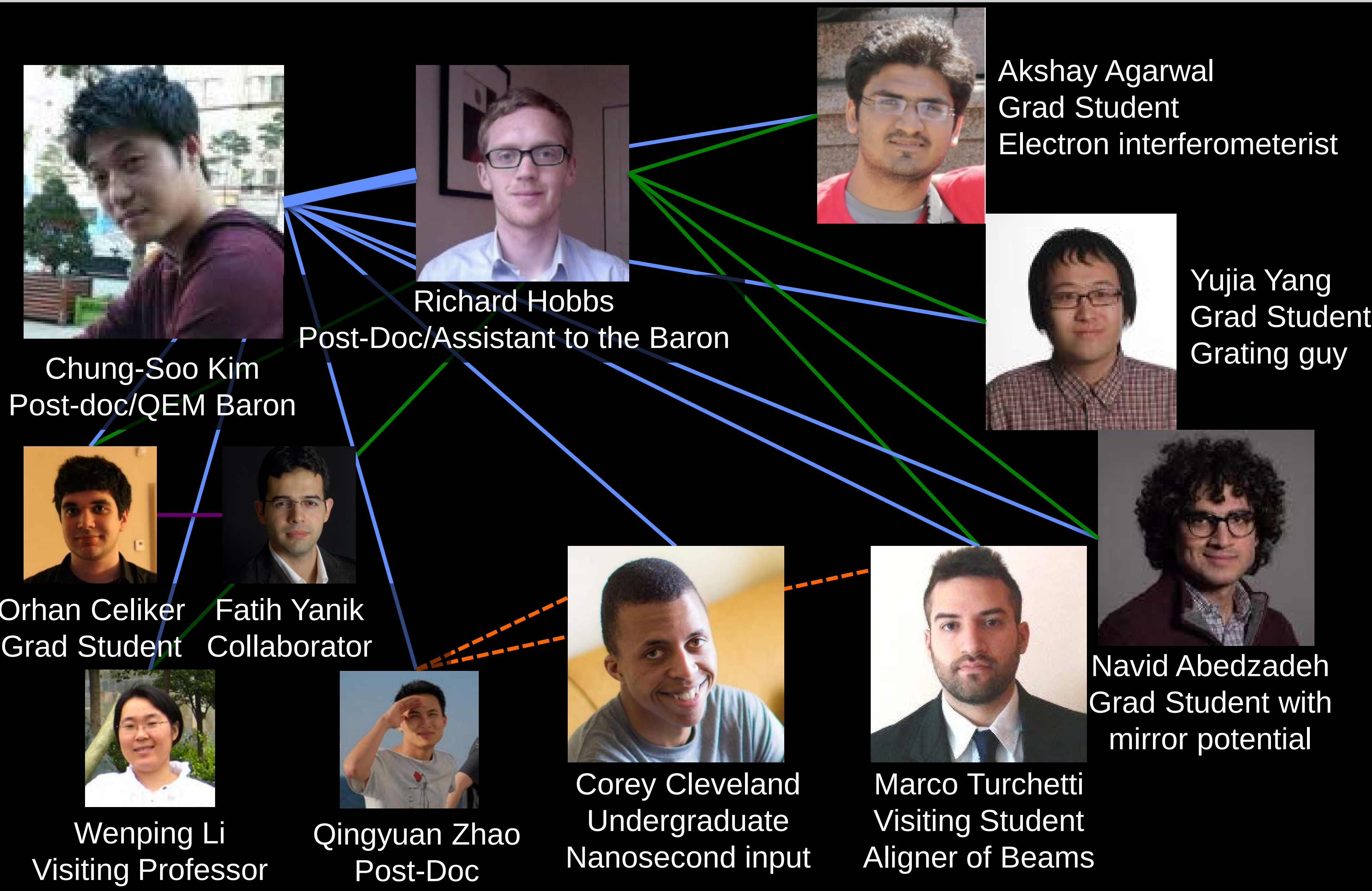
Integrated Electron Cavity in FE-SEM



Summary

- Electron cavity development for “interaction-free” electron microscopy
- Proof of principle electron interferometer for interaction-free measurement
  - Fabrication from single monolithic crystal of silicon
  - Installation in conventional TEM
- Presence of multi-pass electron microscope could be of interest in sensing small phase shifts in electrons for HEP (?)

People at MIT



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